Part IV
Protecting Ground-Water Quality

Chapter 7: Section A
Assessing Risk

Contents

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Assessing Risk

This chapter will help you:

- *Protect ground water by assessing risks associated with new waste management units and tailoring management controls accordingly.*
- *Understand the three-tiered evaluation discussed in this chapter that can be used to determine whether a liner system is necessary, and if so, which liner system is recommended, or whether land application is appropriate.*
- *Follow guidance on liner design and land application practices.*

Table 1.
Earth's Water Resources

Resource	Percent of Total	Percent of Nonoceanic
Oceans	97.25	—
Ice caps and glaciers	2.05	74.65
Ground water and soil moisture	0.685	24.94
Lakes and rivers	0.0101	0.37
Atmosphere	0.001	0.036
Biosphere	0.00004	0.0015

Adapted from Berner, E.K. and R. Berner. 1987. *The Global Water Cycle: Geochemistry and Environment*

Ground water is the water found in the soil and rock that make up the Earth's surface. Although it comprises only about 0.69 percent of the Earth's water resources, ground water is of great importance. It represents about 25 percent of fresh water resources, and when the largely inaccessible fresh water in ice caps and glaciers is discounted, ground water is the Earth's largest fresh water resource—easily surpassing lakes and rivers, as shown in Table 1. Statistics about the use of ground water as a drinking water source underscore the importance of this resource. Ground water is a source of drinking water for more than half of the people in the United States.[1] In rural areas, 97 percent of households rely on ground water as their primary source of drinking water.

In addition to its importance as a domestic water supply, ground water is heavily used by industry and agriculture. It provides approximately 37 percent of the irrigation water and 18 percent of the total water used by industry.[2] Ground water also has other important environmental functions, such as providing recharge to lakes, rivers, wetlands, and estuaries.

Water beneath the ground surface occurs in an upper unsaturated (vadose) zone and a deeper saturated zone. The unsaturated zone is the area above the water table where the soil pores are not filled with water, although some water might be present. The subsurface area below the water table where the pores and cracks are filled with water is called the saturated zone. This chapter focuses on

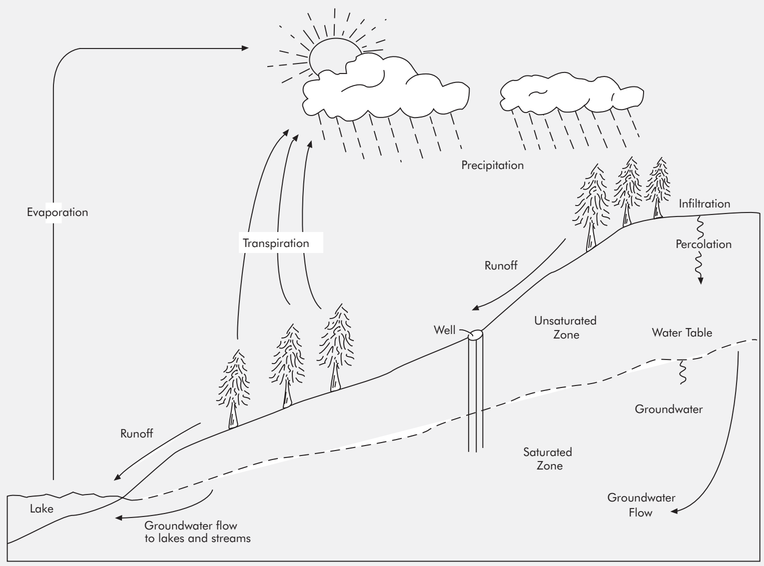
[1] Surface water, in the form of lakes and rivers, is the other major drinking water source. Speidel, D., L. Ruedisili, and A. Agnew. 1988. *Perspectives on Water: Uses and Abuses.*

[2] Excludes cooling water for steam-electric power plants. U.S. Geological Survey. 1998. *Estimated Use of Water in the United States in 1995.*

ground water in the saturated zone, where most ground-water withdrawals are made.

Because ground water is a major source of water for drinking, irrigation, and process water, many different parties are concerned about ground-water contamination, including the public; industry; and federal, state, and local governments. Many potential threats to the quality of ground water exist, such as the leaching of fertilizers and pesticides, contamination from faulty or overloaded septic fields, and releases from industrial facilities, including waste management units.

If a source of ground water becomes contaminated, remedial action and monitoring can be costly. Remediation can require years of effort, or in some circumstances, might be technically infeasible. For these reasons, preventing ground-water contamination is important, or at least minimizing impacts to ground water by implementing controls tailored to the risks associated with the waste.



Ground Water in the Hydrologic Cycle

The hydrologic cycle involves the continuous movement of water between the atmosphere, surface water, and the ground. Ground water must be understood in relation to both surface water and atmospheric moisture. Most additions (recharge) to ground water come from the atmosphere in the form of precipitation, but surface water in streams, rivers, and lakes will move into the ground-water system wherever the hydraulic head of the water surface is higher than the water table. Most water entering the ground as precipitation returns to the atmosphere by evapotranspiration. Most water that reaches the saturated zone eventually returns to the surface by flowing to points of discharge, such as rivers, lakes, or springs. Soil, geology, and climate will determine the amounts and rates of flow among the atmospheric, surface, and ground-water systems.

This chapter addresses how ground-water resources can be protected through the use of a systematic approach of assessing potential risk to ground water from a proposed waste management unit (WMU). It discusses assessing risk and the three-tiered ground-water risk assessment approach implemented in the Industrial Waste Management Evaluation Model (IWEM), which was developed as part of this Guide. Additionally, the chapter discusses the use of this tool and how to apply its results and recommendations. It is highly recommended that you also consult with your state regulatory agency, as appropriate. More specific information on the issues described in this chapter is available in the companion documents to the IWEM software: *User's Guide for the Industrial Waste Management Evaluation Model* (U.S. EPA, 2002b), and *Industrial Waste Management Evaluation Model (IWEM) Technical Background Document* (U.S. EPA, 2002a).

I. Assessing Risk

A. General Overview of the Risk Assessment Process

Our ground-water resources are essential for biotic life on the planet. They also act as a medium for the transport of contaminants and, therefore, constitute an exposure pathway of concern. Leachate from WMUs can be a source of ground-water contamination. Residents who live close to a WMU and who use wells for water supply can be directly exposed to waste constituents by drinking or bathing in contaminated ground water. Residents also can be exposed by inhaling volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) that are released indoors while using ground water for showering or via soil gas migration from subsurface plumes.

The purpose of this section is to provide general information on the risk assessment process and a specific description of how each of the areas of risk assessment is applied in performing ground-water risk analyses. Greater detail on each of the steps in the process as they relate to assessing ground-water risk is provided in later sections of this chapter.

In any risk assessment, there are basic steps that are necessary for gathering and evaluating data. This Guide uses a four-part process to estimate the likelihood of chemicals coming into contact with people now or in the future, and the likelihood that such contact will harm these people. This process shows how great (or small) the risks might be. It also points to who is at risk, what is causing the risk, and how certain one can be about the risks. A general overview of these steps is presented below to help explain how the process is used in performing the assessments associated with IWEM. The components of a risk assessment that are discussed in this section are: problem formulation, exposure assessment, toxicity assessment, and risk characterization. Each of these steps is described as it specifically applies to risk resulting from the release of chemical constituents from WMUs to ground water.

1. Problem Formulation

The first step in the risk assessment process is problem formulation. The purpose of this step is to clearly define the risk question to be answered and identify the objectives, scope, and boundaries of the assessment. This phase can be viewed as developing the overall risk assessment study design for a specific problem. Activities that might occur during this phase include:

- Articulating a clear understanding of the purpose and intended use of the risk assessment.
- Identifying the constituents of concern.
- Identifying potential release scenarios.
- Identifying potential exposure pathways.
- Collecting and reviewing available data.
- Identifying data gaps.
- Recommending data collection efforts.
- Developing a conceptual model of what is occurring at the site.

Although this step can be formal or informal, it is critical to the development of a successful assessment that fully addresses the problem at hand. In addition, the development of a conceptual model helps direct the next phases of the assessment and provides a clear understanding of the scope and design of the assessment.

2. *Exposure Assessment*

The goals of an exposure assessment are to: 1) characterize the source, 2) characterize the physical setting of the area that contains the WMU, 3) identify potential exposure pathways, 4) understand the fate and transport of constituents of concern, and 5) calculate constituent doses.

Source characterization involves defining certain key parameters for the WMU. The accuracy of predicting risks improves as more site-specific information is used in the characterization. In general, critical aspects of the source (e.g., type of WMU, size, location, potential for leachate generation, and expected constituent concentrations in leachate) should be obtained. Knowledge of the overall composition of the waste deposited in the WMU and of any treatment processes occurring in the WMU is important to determine the overall characteristics of the leachate that will be generated.

The second step in evaluating exposure is to characterize the site with respect to its physical characteristics, as well as those of the human populations near the site. Important site characteristics include climate, meteorology, geologic setting, and hydrogeology. Consultation with appropriate technical experts (e.g., hydrogeologists, modelers) might be needed to characterize the site. Characterizing the populations near the site with respect to proximity to the site, activity patterns, and the presence of sensitive subgroups might also be appropriate. This group of data will be useful in determining the potential for exposure to and intake of constituents.

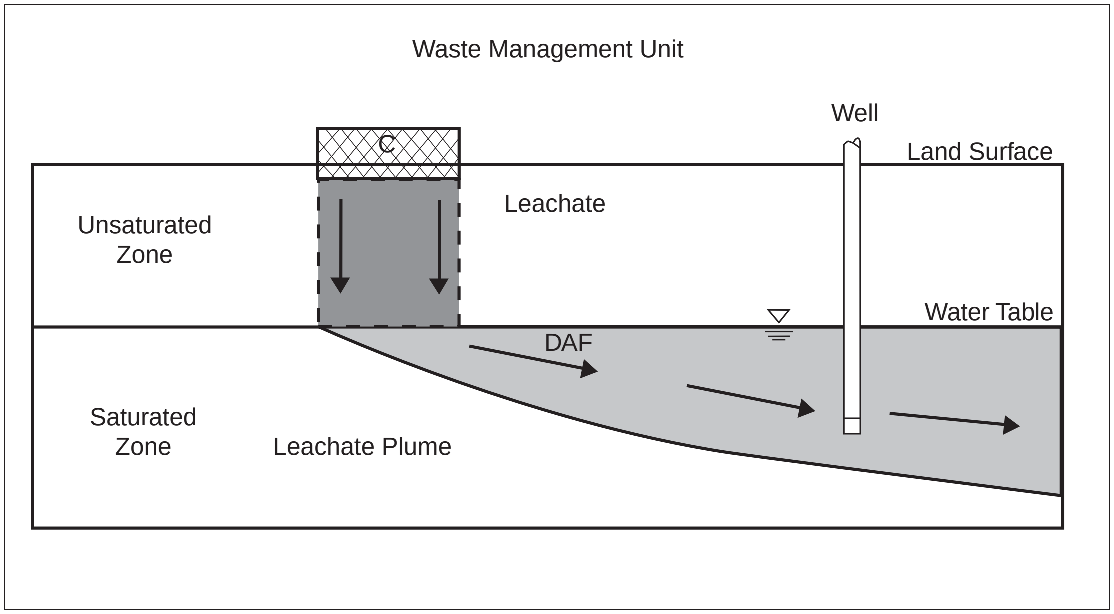
The next step in this process includes identifying exposure pathways through ground water and estimating exposure concentrations at the well[3]. In modeling the movement of the constituents away from the WMU, the Guide generally assumes that the constituents behave as a plume (see Figure 1), and the plume's movement is modeled to produce estimated concentrations of constituents at points of interest. As shown in Figure 1, the unsaturated zone receives leachate from the WMU. In general, the flow in the unsaturated zone tends to be gravity-driven, although other factors (e.g., soil porosity, capillarity, moisture potential) can also influence downward flow.

Transport through the unsaturated zone delivers constituents to the saturated zone, or aquifer. Once the contaminant arrives at the water table, it will be transported downgradient toward wells by the predominant flow field in the saturated zone. The flow field is governed by a number of hydrogeologic and climate-driven factors, including regional hydraulic gradient, hydraulic conductivity of the saturated zone, saturated zone thickness, local recharge rate (which might already be accounted for in the regional hydraulic gradient), and infiltration rate through the WMU.

The next step in the process is to estimate the exposure concentrations at a well. Many processes can occur in the unsaturated zone and in the saturated zone that can influence the concentrations of constituents in leachate in a downgradient well. These processes include dilution and attenuation, partitioning to solid, hydrolysis, and degradation. Typically, these factors should be considered when estimating the expected constituent concentrations at a receptor.

[3] In this discussion and in IWEM, the term "well" is used to represent an actual or hypothetical ground-water monitoring well or drinking water well, located downgradient from a WMU.

Figure 1: Representation of Contaminant Plume Movement



The final step in this process is estimating the dose. The dose is determined based on the concentration of a constituent in a medium and the intake rate of that medium for the receptor. For example, the dose is dependent on the concentration of a constituent in a well and the ingestion rate of ground water from that well by the receptor. The intake rate is dependent on many behavior patterns, including ingestion rate, exposure duration, and exposure frequency. In addition, a risk assessor should consider the various routes of exposure (e.g., ingestion, inhalation) to determine a dose.

After all of this information has been collected, the exposure pathways at the site can be characterized by identifying the potentially exposed populations, exposure media, exposure points, and relevant exposure routes and then calculating potential doses.

3. *Toxicity Assessment*

The purpose of a toxicity assessment is to weigh available evidence regarding the potential for constituents to cause adverse effects in exposed individuals. It is also meant to provide, where possible, an estimate of the relationship between the extent of exposure to a constituent and the increased likelihood and/or severity of adverse effects. The intent is to establish a dose-response relationship between a constituent concentration and the incidence of an adverse effect. It is usually a five-step process that includes: 1) gathering toxicity information for the substances being evaluated, 2) identifying the exposure periods for which toxicity values are necessary, 3) determining the toxicity values for noncarcinogenic effects, 4) determining the toxicity values for carcinogenic effects, and 5) summarizing the toxicity information. The derivation and interpretation of toxicity values requires toxicological expertise and should not be undertaken by those without training and experience. It is recommended that you contact your state regulatory agency for more specific guidance.

4. *Risk Characterization*

This step involves summarizing and integrating the toxicity and exposure assessments and developing qualitative and quantitative expressions of risk. To characterize noncarcinogenic effects, comparisons are made between projected intakes of substances and toxicity values to predict the likelihood that exposure would result in a non-cancer health problem, such as neurological effects. To characterize potential carcinogenic effects, the probability that an individual will develop cancer over a lifetime of exposure is estimated from projected intake and chemical-specific dose-response information. The dose of a particular contaminant to which an individual was exposed—determined during the exposure assessment phase—is combined with the toxicity value to generate a risk estimate. Major assumptions, scientific judgements, and, to the extent possible, estimates of the uncertainties embodied in the assessment are also presented. Risk characterization is a key step in the ultimate decision-making process.

B. Ground-Water Risk

The previous section provided an overview of risk assessment; this section provides more detailed information on conducting a risk assessment specific to ground water. In particular, this section characterizes the phases of a risk assessment—problem formulation, exposure assessment, toxicity assessment, and risk characterization—in the context of a ground-water risk assessment.

1. Problem Formulation

The intent of the problem formulation phase is to define the risk question to be answered. For ground-water risk assessments, the question often relates to whether releases of constituents to the ground water are protective of human health, surface water, or ground-water resources. This section discusses characterizing the waste and developing a conceptual model of a site.

a. Waste Characterization

A critical component in a ground-water risk assessment is the characterization of the leachate released from a WMU. Leachate is the liquid formed when rain or other water comes into contact with waste. The characteristics of the leachate are a function of the composition of the waste and other factors (e.g., volume of infiltration, exposure to differing redox conditions, management of the WMU). Waste characterization includes both identification of the potential constituents in the leachate and understanding the physical and chemical properties of the waste.

Identification of the potential constituents in leachate requires a thorough understanding of the waste that will be placed in a WMU. Potential constituents include those used in typical facility processes, as well as degradation products from these constituents. For ground-water risk analyses, it is important to not only identify the potential constituents of concern in the leachate, but also the likely concentration of these constituents in leachate. To assist in the identification of constituents present in leachate, EPA has developed several leachate tests including the Toxicity Characteristic Leaching Procedure (TCLP), the Synthetic Precipitation Leaching Procedure (SPLP), and the Multiple Extraction Procedure (MEP). These and other tests that can be used to characterize leachate are discussed more fully in Chapter 2—Characterizing Waste and are described in EPA's SW-846 *Test Methods for Evaluating Solid Wastes* (U.S. EPA, 1996 and as updated).

In addition to identifying the constituents present, waste characterization includes understanding the physical, biological, and chemical properties of the waste. The physical and chemical properties of the waste stream affect the likelihood and rate that constituents will move through the WMU. For example, the waste properties influence the partitioning of constituents among the aqueous, vapor, and solid phases. Temperature, pH, pressure, chemical composition,[4] and the presence of microorganisms within WMUs may have significant effects on the concentration of constituents available for release in the leachate. Another waste characteristic that can influence leachate production is the presence of organic wastes as free liquids, also called non-aqueous phase liquids (NAPLs). The presence of NAPLs may affect the mobility of constituents based on saturation and viscosity. Finally, characteristics such as acidity and alkalinity can influence leachate generation by affecting the permeability of underlying soil or clay.

b. Development of a Conceptual Model

The development of a conceptual model is important for defining what is needed for the exposure assessment and the toxicity assessment. The conceptual model identifies the major routes of exposure to be evaluated and presents the current understanding of the toxicity of the constituents of concern.

For the ground-water pathway, the conceptual model identifies those pathways on which the risk assessor should focus. Potential pathways of interest include ground water used as drinking water, ground water used for other domestic purposes that might release volatile organics, ground-water releases to surface water, vapor intrusion from ground-water gases to indoor air, and ground water used as irrigation water. The conceptual model should address the likelihood of various ground-water pathways under present or future circumstances, provide insight to the likelihood of contact with receptors through the various pathways, and identify areas requiring further information.

The conceptual model should also address the toxicity of the constituents of concern. Information about constituent toxicity can be collected from publicly available resources such as the Integrated Risk Information System (IRIS) **<www.epa.gov/iris>** or from detailed, chemical-specific literature searches. The conceptual model should attempt to identify the toxicity data that are most relevant to likely routes of ground-water exposure and identify areas requiring additional research. The conceptual model should provide a draft plan of action for the next phases of the risk assessment.

2. Exposure Assessment

Exposure assessment is generally comprised of two components: characterization of the exposure setting and identification of the exposure pathways. Characterization of the exposure setting includes describing the source characteristics and the site characteristics. Identification of the exposure pathway involves understanding the process by which a constituent is released from a source, travels to a receptor, and is taken up by the receptor. This section discusses the concepts of characterizing the source, characterizing the site setting, understanding the general dynamics of contaminant fate and transport (or movement of harmful chemicals to a receptor), identifying exposure pathways, and calculating the dose to (or uptake by) a receptor.

a. Source Characterization

The characteristics of a source greatly influence the release of leachate to ground water. Some factors to consider include the type of WMU, the size of the unit, and the design and management of the unit. The type of WMU is important because each unit has distinct characteristics that affect release. Landfills, for example, tend to be permanent in nature, which provides a long time period for leachate generation. Waste piles, on the other hand, are temporary in design and

[4] Generally, the model considers a high ratio of solids to leachate, and therefore, the user should consider this before applying a 20 to 1 solids to leachate ratio.

allow the user to remove the source of contaminated leachate at a future date. Surface impoundments, which are generally managed with standing water, provide a constant source of liquid for leachate generation and potentially result in greater volumes of leachate.

The size of the unit is important because units with larger areas have the potential to generate greater volumes of contaminated leachate than units with smaller areas. Also, units such as landfills that are designed with a greater depth below the ground's surface can result in decreased travel time from the bottom of the unit to the water table, resulting in less sorption of constituents. In some cases, a unit might be hydraulically connected with the water table resulting in no attenuation in the unsaturated zone.

The design of the unit is important because it might include an engineered liner system that can reduce the amount of infiltration through the WMU, or a cover that can reduce the amount of water entering the WMU. Typical designs might include compacted clay liners or geosynthetic liners. For surface impoundments, sludge layers from compacted sediments might also help reduce the amount of leachate released. The compacted sediments can have a lower hydraulic conductivity than the natural soils resulting in slower movement of leachate from the bottom of the unit. Covers also affect the rate of leachate generation by limiting the amount of liquid that reaches the waste, thereby limiting the amount of liquid available to form leachate. Co-disposal of different wastes can result in increased or decreased rates of leachate generation. Generally, WMUs with appropriate design specifications can result in reduced leachate generation.

b. Site Characterization

Site characterization addresses the physical characteristics of the site as well as the populations at or near the site. Important physical characteristics include the climate, geology, hydrology, and hydrogeology. These physical characteristics help define the likelihood that water might enter the unit and the likelihood that leachate might travel from the bottom of the unit to the ground water. For example, areas of high rainfall are more likely to generate leachate than arid regions. The geology of the site also can affect the rate of infiltration through the unsaturated zone. For example, areas with fractured bedrock can allow leachate through more quickly than a packed clay material with a low hydraulic conductivity. Hydrology should also be considered because ground water typically discharges to surface water. The presence of surface waters can restrict flow to wells or might require analysis of the impact of contaminated ground water on receptors present in the surface water. Finally, factors related to the hydrogeology, such as the depth to the water table, also influence the rate at which leachate reaches the water table.

The characterization of the site also includes identifying and characterizing populations at or near the site. When characterizing populations, it is important to identify the relative location of the populations to the site. For example, it is important to determine whether receptors are downgradient from the unit and the likely distance from the unit to wells. It is also important to determine typical activity patterns, such as whether ground water is used for drinking water or agricultural purposes. The presence of potential receptors is critical for determining a complete exposure pathway. People might not live there now, but they might live there in 50 years, based on future use assumptions. State or local agencies have relevant information to help you identify areas that are designated as potential sources of underground drinking water.

c. *Understanding Fate and Transport*

In general, the flow in the unsaturated zone tends to be gravity-driven. As shown in Figure 1, the unsaturated zone receives leachate infiltration from the WMU. Therefore, the vertical flow component accounts for most of the fluid flux between the base of the WMU and the water table. Water-borne constituents are carried vertically downward toward the water table by the advection process. Mixing and spreading occur as a result of hydrodynamic dispersion and diffusion. Transport processes in the saturated zone include advection, hydrodynamic dispersion, and sorption. Advection is the process by which constituents are transported by the motion of the flowing ground water. Hydrodynamic dispersion is the tendency for some constituents to spread out from the path that they would be expected to flow. Sorption is the process by which leachate molecules adhere to the surface of individual clay, soil, or sediment particles. Attenuation of some chemicals in the unsaturated zone is attributable to various biochemical or physicochemical processes, such as degradation and sorption.

The type of geological material below the unit affects the rate of movement because of differences in hydraulic and transport properties. One of the key parameters controlling contaminant migration rates is hydraulic conductivity. The larger the hydraulic conductivity, the greater the potential migration rate due to lower hydraulic resistance of the formation. Hydraulic conductivity values of some hydrogeologic environments, such as bedded sedimentary rock aquifers, might not be as large as those of other hydrogeologic environments, such as sand and gravel or fractured limestone. As a general principle, more rapid movement of waste constituents can be expected through coarse-textured materials, such as sand and gravel, than through fine-textured materials, such as silt and clay. Other key flow and transport parameters include dispersivity (which determines how far a plume will spread horizontally and vertically as it moves away from the source) and porosity (which determines the amount of pore space in the geologic materials in the unsaturated and saturated zone used for flow and transport and can affect transport velocity).

As waste constituents migrate through the unsaturated and saturated zones, they can undergo a number of biochemical and physicochemical processes that can lead to a reduction in concentration of potential ground-water contaminants. These processes are collectively referred to as attenuation processes. Attenuation processes can remove or degrade waste constituents through filtration, sorption, precipitation, hydrolysis, biological degradation, bio-uptake, and redox reactions. Some of these processes (e.g., hydrolysis, biological degradation) can actually result in the formation of different chemicals and greater toxicity. Attenuation processes are dependent upon several factors, including ground-water pH, ground-water temperature, and the presence of other compounds in the subsurface environment. Table 2 provides additional information on attenuation processes.

d. *Exposure Pathways*

A complete exposure pathway usually consists of four elements: 1) a source and mechanism of chemical release, 2) a retention or transport medium (in this case, ground water), 3) a point of potential human contact with the contaminated medium (often referred to as the exposure point), and 4) an exposure route (e.g., ingestion). Residents who live near

Table 2:
Examples of Attenuation Processes

Biological degradation: Decomposition of a substance into more elementary compounds by action of microorganisms such as bacteria. Sullivan. 1993. *Environmental Regulatory Glossary*, 6th Ed. Government Institutes.

Bio-uptake: The uptake and (at least temporary) storage of a chemical by an exposed organism. The chemical can be retained in its original form and/or modified by enzymatic and non-enzymatic reactions in the body. Typically, the concentrations of the substance in the organism exceed the concentrations in the environment since the organism will store the substance and not excrete it. Sullivan. 1993. *Environmental Regulatory Glossary*, 6th Ed. Government Institutes.

Filtration: Physical process whereby solid particles and large dissolved molecules suspended in a fluid are entrapped or removed by the pore spaces of the soil and aquifer media. Boulding, R. 1995. *Soil, Vadose Zone, and Ground-Water Contamination: Assessment, Prevention, and Remediation.*

Hydrolysis: A chemical process of decomposition in which the elements of water react with another substance to yield one or more entirely new substances. This transformation process changes the chemical structure of the substance. Sullivan. 1993. *Environmental Regulatory Glossary*, 6th Ed. Government Institutes.

Oxidation/Reduction (Redox) reactions: Involve a transfer of electrons and, therefore, a change in the oxidation state of elements. The chemical properties for elements can change substantially with changes in the oxidation state. U.S. EPA. 1991. *Site Characterization for Subsurface Remediation.*

Precipitation: Chemical or physical change whereby a contaminant moves from a dissolved form in a solution to a solid or insoluble form. It reduces the mobility of constituents, such as metals. Unlike sorption, precipitation is not generally reversible. Boulding, R. 1995. *Soil, Vadose Zone, and Ground-Water Contamination: Assessment, Prevention, and Remediation.*

Sorption: The ability of a chemical to partition between the liquid and solid phase by determining its affinity for adhering to other solids in the system such as soils or sediments. The amount of chemical that "sorbs" to solids is dependent upon the characteristics of the chemical, the characteristics of the surrounding soils and sediments, and the quantity of the chemical. Sorption generally is reversible. Sorption often includes both adsorption and ion exchange.

a site might use ground water for their water supply, and thus, the exposure point would be a well. Exposure routes typical of residential use of contaminated ground water include direct ingestion through drinking water, dermal contact while bathing, and inhalation of VOCs during showering or from other household water uses (e.g., dishwashers).

Another potential pathway of concern is exposure to ground-water constituents from the intrusion of vapors of VOCs and SVOCs through the basements and concrete slabs beneath houses. This pathway is characterized by the vapors seeping into households through the cracks and holes in basements and concrete slabs. In some cases, concentrations of constituents can reach levels that present chronic health hazards. Factors that can contribute to the potential for vapor intrusion include the types of constituents present in the ground water, the presence of pavement or frozen surface soils (which result in higher subsurface pressure gradients and greater transport), and the presence of subsurface gases such as methane that affect the rate of transport of other constituents. Because of the complexity of this pathway and the evolving science regarding this pathway, IWEM focuses on the risks and pathways associated with residential exposures to contaminated ground water. If exposure through this route is likely, the user might consider Tier 3 modeling to assess this pathway. EPA is planning to issue a reference document regarding the vapor intrusion pathway in the near future.

e. Dose Calculation

The final element of the exposure assessment is the dose calculation. The dose to a receptor is a function of the concentration at the exposure point (i.e, the well) and the intake rate by the receptor. The concentration at the exposure point is based on the release from the source and the fate and transport of the constituent. The intake rate is dependent on the exposure route, the frequency of exposure, and the duration of exposure.

EPA produced the *Exposure Factors Handbook* (U.S. EPA, 1997a) as a reference for providing a consistent set of exposure factors to calculate the dose. This reference is available from EPA's National Center for Environmental Assessment Web site **<www.epa.gov/ncea>**. The purpose of the handbook is to summarize data on human behaviors and physical characteristics (e.g., body weight) that affect exposure to environmental contaminants and recommend values to use for these factors. The result of a dose calculation is expressed as a contaminant concentration per unit body weight per unit time that can then be used as the output of the exposure assessment for the risk characterization phase of the analysis.

3. Toxicity Assessment

A toxicity assessment weighs available evidence regarding the potential for particular contaminants to cause adverse effects in exposed individuals, and where possible, provides an estimate of the increased likelihood and severity of adverse effects as a result of exposure to a contaminant. IWEM uses two different toxicity measures—maximum contaminant levels (MCLs) and health-based numbers (HBNs). Each of these measures is based on toxicity values reflecting a cancer or noncancer effect. Toxicity data are based on human epidemiologic data, animal data, or other supporting studies (e.g., laboratory studies). In general, data can be used to characterize the potential adverse effect of a constituent as either carcinogenic or non-carcinogenic. For the carcinogenic effect, EPA generally assumes there is a non-threshold effect and estimates a risk per unit dose. For the noncarcinogenic effect, EPA generally assumes there is a threshold below which no adverse effects occur. The toxicity values used in IWEM include:

- Oral cancer slope factors (CSFo) for oral exposure to carcinogenic contaminants.
- Reference doses (RfD) for oral exposure to contaminants that cause noncancer health effects.
- Inhalation cancer slope factors (CSFi) derived from Unit Risk Factors (URFs) for inhalation exposure to carcinogenic contaminants.
- Reference concentrations (RfC) for inhalation exposure to contaminants that cause noncancer health effects.

EPA defines the cancer slope factor (CSF) as, "an upper bound, approximating a 95 percent confidence limit, on the increased cancer risk from a lifetime exposure to an agent [contaminant]." Because the CSF is an upper bound estimate of increased risk, EPA is reasonably confident that the "true risk" will not exceed the risk estimate derived using the CSF and that the "true risk" is likely to be less than predicted. CSFs are expressed in units of proportion (of a population) affected per milligram/kilogram-day (mg/kg-day). For noncancer health effects, the RfD and the RfC are used as health benchmarks for ingestion and inhalation exposures, respectively. RfDs and RfCs are estimates of daily oral exposure or of continuous inhalation exposure, respectively, that are likely to be without an appreciable risk of adverse effects in the general population, including sensitive individuals, over a lifetime. The methodology used to develop RfDs and RfCs is expected to have an uncertainty spanning an order of magnitude.

a. *Maximum Contaminant Levels (MCLs)*

MCLs are maximum permissible contaminant concentrations allowed in public drinking water and are established under the Safe Drinking Water Act. For each constituent to be regulated, EPA first sets a Maximum Contaminant Level Goal (MCLG) as a level that protects against health risks. The MCL for each contaminant is then set as close to its MCLG as possible. In developing MCLs, EPA considers not only the health effects of the constituents, but also additional factors, such as the cost of treatment, available analytical and treatment technologies. Table 3 lists the 57 constituents that have MCLs that are incorporated in IWEM.

b. *Health-based Numbers (HBNs).*

The parameters that describe a chemical's toxicity and a receptor's exposure to the chemical are considered in calculation of the HBN(s) of that chemical. HBNs are the maximum contaminant concentrations in ground water that are not expected to cause adverse noncancer health effects in the general population (including sensitive subgroups) or that will not result in an additional incidence of cancer in more than approximately one in one million individuals exposed to the contaminant. Lower concentrations of the contaminant are not likely to cause adverse health effects. Exceptions might occur, however, in individuals exposed to multiple contaminants that produce the same health effect. Similarly, a higher incidence of cancer among sensitive subgroups, highly exposed subpopulations, or populations exposed to more than one cancer-causing contaminant might be expected. As noted previously, the exposure factors used to calculate HBNs are described in the *Exposure Factors Handbook* (U.S. EPA, 1997a).

4. *Risk Characterization*

Risk characterization is the integration of the exposure assessment and the toxicity assessment to generate qualitative and quantitative expressions of risk. For carcinogens, the target risk level used in IWEM to calculate the HBNs is 1×10^{-6}. A risk of 1×10^{-6} describes an increased chance of one in a million of a person developing cancer over a lifetime, due to chronic exposure to a specific chemical. The target hazard quotient used to calculate the HBNs for noncarcinogens is 1. A hazard quotient of 1 indicates that the estimated dose is equal to the RfD (the level below which no adverse effect is expected). An HQ of 1, therefore, is frequently EPA's threshold of concern for noncancer effects. These targets are used to calculate unique HBNs for each constituent of concern and each exposure route of concern (i.e., ingestion or inhalation).

Usually, doses less than the RfD (HQ = 1) are not likely to be associated with adverse health effects and, therefore, are less likely to be of regulatory concern. As the frequency or magnitude of the exposures exceeding the RfD increase (HQ > 1), the probability of adverse effects in a human population increases. However, it should not be categorically concluded that all doses below the RfD

Table 3.
List of Constituents in IWEM with Maximum Contaminant Levels (MCLs)

(States can have more stringent standards than federal MCLs.)

Organics with an MCL	mg/l		mg/l
Benzene	0.005	HCH (Lindane) gamma-	0.0002
Benzo[a]pyrene	0.0002	Heptachlor	0.0004
Bis(2-ethylhexyl)phthalate	0.006	Heptachlor epoxide	0.0002
Bromodichloromethane*	0.10	Hexachlorobenzene	0.001
Butyl-4,6-dinitrophenol,2-sec-(Dinoseb)	0.007	Hexachlorocyclopentadiene	0.05
Carbon tetrachloride	0.005	Methoxychlor	0.04
Chlordane	0.002	Methylene chloride (Dichloromethane)	0.005
Chlorobenzene	0.1	Pentachlorophenol	0.001
Chlorodibromomethane*	0.10	Polychlorinated biphenyls (PCBs)	0.0005
Chloroform*	0.10	Styrene	0.1
Dibromo-3-chloropropane 1,2-(DBCP)	0.0002	TCD Dioxin 2,3,7,8-	0.00000003
Dichlorobenzene 1,2-	0.6	Tetrachloroethylene	0.005
Dichlorobenzene 1,4-	0.075	Toluene	1
Dichloroethane 1,2-	0.005	Toxaphene (chlorinated camphenes)	0.003
Dichloroethylene cis-1,2-	0.07	Tribromomethane (Bromoform)*	0.10
Dichloroethylene trans-1,2-	0.1	Trichlorobenzene 1,2,4-	0.07
Dichloroethylene 1,1-(Vinylidene chloride)	0.007	Trichloroethane 1,1,1-	0.2
Dichlorophenoxyacetic acid 2,4- (2,4-D)	0.07	Trichloroethane 1,1,2-	0.005
Dichloropropane 1,2-	0.005	Trichloroethylene (1,1,2- Trichloroethylene)	0.005
Endrin	0.002	2,4,5-TP (Silvex)	0.05
Ethylbenzene	0.7	Vinyl chloride	0.002
Ethylene dibromide (1,2- Dibromoethane)	0.00005	Xylenes	10
Inorganics with an MCL			
Antimony	0.006	Copper***	1.3
Arsenic**	0.05	Fluoride	4.0
Barium	2.0	Lead***	0.015
Beryllium	0.004	Mercury (inorganic)	0.002
Cadmium	0.005	Selenium	0.05
Chromium (total used for Cr III and Cr VI)	0.1	Thallium	0.002

For list of current MCLs, visit: **<www.epa.gov/safewater/mcl.html>**
* Listed as Total Trihalomethanes (TTHMs), constituents do not have individually listed MCLs
** Arsenic standard will be lowered to 0.01 mg/L by 2006.
*** Value is drinking water "action level" as specified by 40 CFR 141.32(e) (13) and (14).

are "acceptable" (or will be risk-free) and that all doses in excess of the RfD are "unacceptable" (or will result in adverse effects). For IWEM, the output from the risk characterization helps determine with 90 percent probability (i.e., with a confidence that for 90 percent of the realizations) whether or not a design system is protective (i.e., has a cancer risk of $< 1 \times 10^{-6}$, non-cancer hazard quotient of < 1.0). IWEM does not address the cumulative risk due to simultaneous exposure to multiple constituents. The results of the risk assessment might encourage the user to conduct a more site-specific analysis, or consider opportunities for waste minimization or pollution prevention.

II. The IWEM Ground-Water Risk Evaluation

This section takes the principles of risk assessment described in Part I and applies them to evaluating industrial waste management unit liner designs. This is accomplished using IWEM and a three-tiered ground-water modeling approach to make recommendations regarding the liner design systems that should be considered for a potential unit, if a liner design system is considered necessary. The tiered approach was chosen to provide facility managers, the public, and state regulators flexibility in assessing the appropriateness of particular WMU designs as the user moves from a national assessment to an assessment using site-specific parameters.

The three tiers allow for three possible approaches. The first approach is a quick screening tool, a set of lookup tables, which provides conservative national criteria. While this approach, labeled Tier 1, does not take into account site- (or even state-) specific conditions, it does provide a rapid and easy screening. If the use of Tier 1 provides an agreeable assessment, the conservative nature of the model can be relied upon, and the additional resources required for further analysis can be avoided. Of course, where there is concern with the results from Tier 1, a more precise assessment of risk at the planned unit location should be conducted. The second approach is to try and accommodate many of the most important site-specific factors in a simplified form, useable by industry, state, and environmental representatives. This model, labeled Tier 2, is available as part of this Guide, and is a major new step in moving EPA guidance away from national, "one size fits all" approaches. Third, a site-specific risk analysis can be conducted. This approach should provide the most precise assessment of the risks posed by the planned unit. Such an analysis, labeled Tier 3, should be conducted by experts in ground-water modeling, and can require significant resources. This Guide identifies the benefits and sources for selecting site-specific models, but does not provide such models as part of this Guide. In many cases, corporations will go directly to conducting the more exacting Tier 3 analysis, which EPA believes is acceptable under the Guide. There is, however, still a need for the Tier 2 tool. State and environmental representatives might have limited resources to conduct or examine a Tier 3 assessment; Tier 2 can provide a point of comparison with the results of the Tier 3 analysis, narrow the technical discussion to those factors which are different in the models, and form a basis for a more informed dialogue on the reasonableness of the differences.

IWEM is designed to address Tier 1 and Tier 2 evaluations. Both tiers of the tool consider all portions of the risk assessment process (i.e., problem formulation, exposure assessment, toxicity assessment, and risk characterization) to generate results that vary from a national-level screening evaluation to a site-specific assessment. The Tier 3 evaluation is a complex, site-specific hydrogeologic investigation that would be performed with other models such as those listed at the end of this chapter. Those models could be used to evaluate hydrogeological complexities that are not addressed by IWEM. Brief outlines of the three tiers follow.

A Tier 1 evaluation involves comparing the expected leachate concentrations of wastes being assessed against a set of pre-calculated maximum recommended leachate concentrations (or Leachate Concentration Threshold Values—LCTVs). The Tier 1 LCTVs are nationwide, ground-water fate and transport modeling results from EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP). EPACMTP simulates the fate and transport of leachate infiltrating from the bottom of a WMU and predicts concentrations of those contaminants in a well. In making these predictions, the model quantitatively accounts for many complex processes that dilute and attenuate the concentrations of waste constituents as they move through the subsurface to the well. The results that are generated show whether a liner system is considered necessary, and if so which liner systems will be protective for the constituents of concern. Tier 1 results are designed to be protective with 90 percent certainty at a $1x10^{-6}$ risk level for carcinogens or a noncancer hazard quotient of < 1.0.

The Tier 2 evaluation incorporates a limited number of site-specific parameters to help provide recommendations about which liner system (if any is considered necessary) is protective for constituents of concern in settings that are more reflective of your site. IWEM is designed to facilitate site-specific simulations without requiring the user to have any previous ground-water modeling experience. As with any ground-water risk evaluation, however, the user is advised to discuss the results of the Tier 2 evaluation with the appropriate state regulatory agency before selecting a liner design for a new WMU.

If the Tier 1 and Tier 2 modeling do not adequately simulate conditions at a proposed site because the hydrogeology of the site is complex, or because the user believes Tier 2 does not adequately address a particular site-specific parameter, the user is advised to consider a more in-depth, site-specific risk assessment. This Tier 3 assessment involves a more detailed, site-specific ground-water fate and transport analysis. The user should consult with state officials and appropriate trade associations to solicit recommendations for approaches for the analysis.

The remainder of this section discusses in greater detail how to use IWEM to perform a Tier 1 or Tier 2 evaluation. In addition, this section presents information concerning the use of Tier 3 models.

A. The Industrial Waste Management Evaluation Model (IWEM)

The IWEM is the ground-water modeling component of the *Guide for Industrial Waste Management*, used for recommending appropriate liner system designs, where they are considered necessary, for the management of RCRA Subtitle D industrial waste. IWEM compares the expected leachate concentration (entered by the user) for each waste constituent with a protective level calculated by a ground-water fate and transport model to determine whether a liner system is needed. When IWEM determines a liner system is necessary, it then evaluates two standard liner types (i.e., single clay-liner and composite liner). This section discusses components of the tool and important concepts whose understanding is necessary for its effective use. The user can refer to the *User's Guide for the*

Industrial Waste Management Evaluation Model (U.S. EPA, 2002b) for information necessary to perform Tier 1 and Tier 2 analyses, and the *Industrial Waste Management Evaluation Model Technical Background Document* (U.S. EPA, 2002a), for more information on the use and development of IWEM.

1. Leachate Concentrations

The first step in determining a protective waste management unit design is to identify the expected constituents in the waste and expected leachate concentrations from the waste. In order to assess ground-water risks using either the Tier 1 or Tier 2 evaluations provided in IWEM, the expected leachate concentration for each individual constituent of interest must be entered into the model. See Chapter 2—Characterizing Wastes, for a detailed discussion of the various approaches available to use in evaluating expected leachate concentrations.

2. Models Associated with IWEM

One of the highlights of IWEM is its ability to simulate the fate and transport of waste constituents at a WMU with a small number of site-specific inputs. To accomplish this task, IWEM incorporates the outputs of three other models, specifically EPACMTP, MINTEQA2, and HELP. This section discusses these three models.

a. EPACMTP

EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) is the backbone of IWEM. EPACMTP is designed to simulate subsurface fate and transport of contaminants leaching from the bottom of a WMU and predict concentrations of those contaminants in a downgradient well. In making these predictions, the model accounts for many complex processes that occur as waste constituents and their transformation products move to and through ground water. As leachate carrying waste constituents migrates through the unsaturated zone to the water table, attenuation processes, such as adsorption and degradation, reduce constituent concentrations. Ground-water transport in the saturated zone further reduces leachate concentrations through dilution and attenuation. The concentration of constituents arriving at a well, therefore, is lower than that in the leachate released from a WMU.

In the unsaturated zone, the model simulates one-dimensional vertical migration with steady infiltration of constituents from the WMU. In the saturated zone, EPACMTP simulates three-dimensional plume-movement (i.e., horizontal as well as transverse and vertical spreading of a contaminant plume). The model considers not only the subsurface fate and transport of constituents, but also the formation and the fate and transport of transformation (daughter and granddaughter) products. The model also can simulate the fate and transport of metals, taking into account geochemical influences on the mobility of metals.

b. MINTEQA2

In the subsurface, metal contaminants can undergo reactions with other substances in the ground water and with the solid aquifer or soil matrix material. Reactions in which the metal is bound to the solid matrix are referred to as sorption reactions, and the metal bound to the solid is said to be sorbed. During contaminant transport, sorption to the solid matrix results in retardation (slower movement) of the contaminant front. Transport models such as EPACMTP incorporate a retardation factor to account for sorption processes.

The actual geochemical processes that control the sorption of metals can be quite complex, and are influenced by factors such as pH, the type and concentration of the metal in the leachate plume, the presence and concentrations of other constituents in the leachate plume, and other factors. The EPACMTP model is not capable of simulating all these processes in detail. Another model, MINTEQA2[5], is used to determine a sorption coefficient for each of the metals species. For IWEM, distributions of variables (e.g., leachable organic matter, pH) were used to generate a distribution of isotherms for each metal species. EPACMTP, in turn, samples from these calculated sorption coefficients and uses the selected isotherm as a modeling input to account for the effects of nationwide or aquifer-specific ground-water and leachate geochemistry on the sorption and mobility of metals constituents.

c. HELP

The Hydrologic Evaluation of Landfill Performance (HELP) model is a quasi-two-dimensional hydrologic model for computing water balances of landfills, cover systems, and other solid waste management facilities. The primary purpose of the model is to assist in the comparison of design alternatives. HELP uses weather, soil, and design data to compute a water balance for landfill systems accounting for the effects of surface storage; snowmelt; runoff; infiltration; evapotranspiration; vegetative growth; soil moisture storage; lateral subsurface drainage; leachate recirculation; unsaturated vertical drainage; and leakage through soil, geomembrane, or composite liners. The HELP model can simulate landfill systems consisting of various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners. For further information on the HELP model, visit: **<wes.army.mil/el/elmodels/helpinfo.html>**.

For the application of HELP to IWEM, an existing database of infiltration and recharge rates was used for 97 climate stations in the lower 48 contiguous states. Five climate stations (located in Alaska, Hawaii, and Puerto Rico) were added to ensure coverage throughout all of the United States. These climatic data were then used along with data on the soil type and WMU design characteristics, to calculate a water balance for each applicable liner design as a function of the amount of precipitation that reaches the surface of the unit, minus the amount of runoff and evapotranspiration. The HELP model then computed the net amount of water that infiltrates through the surface of the unit (accounting for recharge), the waste, and the unit's bottom layer (for unsaturated soil and clay liner scenarios only), based on the initial moisture content and the hydraulic conductivity of each layer.

Although data were collected for all 102 sites, these data were only used for the unlined landfills, waste piles, and land application units. For the clay liner scenarios (landfills and waste piles only), EPA grouped sites and ran the HELP model only for a subset of the facilities that were representative of the ranges of precipitation, evaporation, and soil type. The grouping is discussed further in the *IWEM Technical Background Document* (U.S. EPA, 2002a).

In addition to climate factors and the particular unit design, the infiltration rates calculated by HELP are affected by the landfill cover design, the permeability of the waste material in waste piles, and the soil type of the land application unit. For every climate station and WMU design, multiple HELP infiltration rates are calculated. In Tier 1, for a selected WMU type and design, the EPACMTP Monte Carlo modeling process was used to randomly select from among the HELP-derived infiltration and recharge data.

[5] MINTEQA2 is a geochemical equilibrium speciation model for computing equilibria among the dissolved, absorbed, solid, and gas phases in dilute aqueous solution.

This process captured both the nationwide variation in climate conditions and variations in soil type. In Tier 2, the WMU location is a required user input, and the climate factors used in HELP are fixed. However, in Tier 2, the Monte Carlo process is still used to account for local variability in the soil type, landfill cover design, and permeability of waste placed in waste piles.

3. Important Concepts for Use of IWEM

Several important concepts are critical to understanding how IWEM functions. These concepts include 90th percentile exposure concentration, dilution and attenuations factors (DAFs), reference ground-water concentrations (RGCs), leachate concentration threshold values (LCTVs), and units designs.

a. 90th Percentile Exposure Concentration

The 90th percentile exposure concentration was chosen to represent the estimated constituent concentration at a well for a given leachate concentration. The 90th percentile exposure concentration was selected because this concentration is protective for 90 percent of the model simulations conducted for a Tier 1 or Tier 2 analysis. In Tier 1, the 90th percentile concentration is used to calculate a DAF, which is then used to generate a leachate concentration threshold value (LCTV). In Tier 2, the 90th percentile concentration is directly compared with a reference ground-water concentration to determine whether a liner system is necessary, and if so whether the particular liner design is protective for a site.

The 90th percentile exposure concentration is determined by running EPACMTP in a Monte Carlo mode for 10,000 realizations. For each realization, EPACMTP calculates a maximum average concentration at a well, depending on the exposure duration of the reference ground-water concentration (RGC) of interest. For example, IWEM assumes a 30-year exposure duration for carcinogens, and therefore, the maximum average concentration is the highest 30-year average across the modeling horizon. After calculating the maximum average concentrations across the 10,000 realizations, the concentrations are arrayed from lowest to highest and the 90th percentile of this distribution is selected as the constituent concentration for IWEM.

Once the 90th percentile exposure concentration is determined, it is used in one of two ways. For both the Tier 1 analysis and the Tier 2 analysis, the 90th percentile exposure concentration is compared with the expected waste leachate concentration to generate a DAF. This calculation is discussed further in the following section. For Tier 2, the 90th percentile exposure concentration is the concentration of interest for the analysis. The 90th percentile exposure concentration can be directly compared with the reference ground-water concentration to assist in waste management decision-making.

b. Dilution and Attenuation Factors

DAFs represent the expected reduction in waste constituent concentration resulting from fate and transport in the subsurface. A DAF is defined as the ratio of the constituent concentration in the waste leachate to the concentration at the well, or:

$$DAF = \frac{C_L}{C_W}$$

where: DAF is the dilution and attenuation factor;

C_L is the leachate concentration (mg/L); and

C_W is the ground-water well concentration (mg/L).

The magnitude of a DAF reflects the combined effect of all dilution and attenuation processes that occur in the unsaturated and saturated zones. The lowest possible value of a DAF is one. A DAF of 1 means that there is no dilution or attenuation at all; the concentration at a well is the same as that in the waste leachate. High DAF values, on the other hand, correspond to a high degree of dilution and attenuation. This means that the expected concentration at the well will be much lower than the concentration in the leachate. For any specific site, the DAF depends on the interaction of waste constituent characteristics (e.g., whether or not the constituent degrades or sorbs), site-specific factors (e.g., depth to ground water, hydrogeology), and physical and chemical processes in the subsurface environment. In addition, the DAF calculation does not take into account when the exposure occurs, as long as it is within a 10,000-year time-frame following the initial release of leachate. Thus, if two constituents have different mobility, the first might reach the well in 10 years, while the second constituent might not reach the well for several hundred years. EPACMTP, however, can calculate the same or very similar DAF values for both constituents.

For the Tier 1 analysis in IWEM, DAFs are based on the 90th percentile exposure concentration. EPACMTP was implemented by randomly selecting one of the settings from the WMU database and assigning a unit leachate concentration to each site until 10,000 runs had been conducted for a WMU. The resulting 10,000 maximum well concentrations based on the averaging period associated with the exposure duration of interest (i.e., 1-year, 7-years, 30-years) were then arrayed from lowest to highest. The 90th percentile concentration of this distribution is then used as the concentration in the ground-water well (Cw) for calculating the DAF. The DAF is similarly calculated for the Tier 2, but because the site-specific leachate concentration is used in the EPACMTP model runs, the 90th percentile exposure concentration can be compared directly to the RGC.

c. *Reference Ground-Water Concentration (RGC)*

As used in this Guide and by IWEM, a reference ground-water concentration (RGC) is defined as a constituent concentration threshold in a well that is protective of human health. RGCs have been developed based on maximum contaminant levels (MCLs) and health-based-numbers (HBN). Each constituent can have up to five RGCs: 1) based on an MCL, 2) based on carcinogenic effects from ingestion, 3) based on carcinogenic effects from inhalation while showering, 4) based on non-carcinogenic effects from ingestion, and 5) based on non-carcinogenic effects from inhalation while showering.

The IWEM's database includes 226 constituents with at least one RGC. Of the 226 constituents, 57 have MCLs (see Table 3), 212 have ground-water ingestion HBNs, 139 have inhalation HBNs, and 57 have both an MCL and HBN. The HBNs were developed using standard EPA exposure assumptions for residential receptors. For carcinogens, IWEM used a target risk level equal to the probability that there might be one increased cancer case per one million exposed people (commonly referred to as a $1x10^{-6}$ cancer risk). The target hazard quotient used to calculate the HBNs for noncarcinogens was 1 (unitless). A hazard quotient of 1 indicates that the estimated dose is equal to the oral reference dose (RfD) or inhalation reference concentration (RfC). These targets were used to calculate unique HBNs for each constituent of concern and each exposure route of concern (ingestion or inhalation). For further information on the derivation of the IWEM RGCs, see the *Industrial Waste Management Evaluation Model Technical Background*

Document (U.S. EPA, 2002a). Users also can add new constituents and RGCs can vary depending on the protective goal. For example, states can impose more stringent drinking water standards than federal MCLs.[6] To keep the software developed for this Guide up-to-date, and to accommodate concerns at levels different from the current RGCs, the RGC values in the IWEM software tool can be modified by the user of the software.

d. *Leachate Concentration Threshold Values (LCTVs)*

The purpose of the Tier 1 analysis in IWEM is to determine whether a liner system is needed, and if so, to recommend liner system designs or determine the appropriateness of land application with minimal site-specific data. These recommendations are based on LCTVs that were calculated to be protective for each waste constituent in a unit. These LCTVs are the maximum leachate concentrations for which water in a well is not likely to exceed the corresponding RGC. The LCTV for each constituent accounts for dilution and attenuation in the unsaturated and saturated zones prior to reaching a well. An LCTV has been generated for a no liner/in situ soils scenario and for two standard liner types (i.e., single clay liner and composite liner) and each RGC developed for a constituent.

The LCTV for a specific constituent is the product of the RGC and the DAF:

LCTV = DAF * MCL

or LCTV = DAF * HBN

Where: LCTV is the leachate concentration threshold value

DAF is the dilution and attenuation factor

MCL is the maximum concentration level

HBN is the health-based number

The evaluation of whether a liner system is needed and subsequent liner system design recommendations is determined by comparing the expected waste constituent leachate concentrations to the corresponding calculated LCTVs. LCTVs are calculated for all unit types (i.e., landfills, waste piles, surface impoundments, land application units) by type of design (i.e., no liner/in situ soils, single liner, or composite liner).[7] The Tier 1 evaluation is generally the most protective and calculates LCTVs using data collected on WMUs throughout the United States.[8] LCTVs used in Tier 1 are designed to be protective to a level of $1x10^{-6}$ for carcinogens or a noncancer hazard quotient of < 1.0 with a 90 percent certainty considering the range of variability associated with the waste sites across the United States. LCTVs from the Tier 1 analysis are generally applicable to sites across the country; users can determine whether a specific liner design for a WMU is protective by comparing expected leachate concentrations for constituents in their waste with the LCTVs for each liner design.

The Tier 2 analysis differs from the Tier 1 analysis in that IWEM calculates a site-specific DAF in Tier 2. This allows the model to calculate a site-specific 90th percentile exposure concentration that can be compared with an RGC to determine if a liner system is needed and to recommend the appropriate liner system if necessary. The additional calculation of an LCTV is not necessary. IWEM continues to perform the calculation, however, to help users determine whether waste minimization might be appropriate to meet a specific design. For example, a facility might

[6] For example, a state can make secondary MCLs mandatory, which are not federally enforceable standards, or a state might use different exposure assumptions, which can result in a different HBN. In addition, states can choose to use a different risk target than is used in this Guidance.

[7] LCTVs are influenced by liner designs because of different infiltration rates.

[8] For additional information on the nationwide data used in the modeling, see the *IWEM Technical Background Document* (U.S. EPA, 2002a).

find it more cost effective to reduce the concentration of constituents in its waste and design a clay-lined landfill than to dispose of the current waste in a composite landfill. The LCTV calculated for the Tier 2 analysis is based on the expected leachate concentration for a specific site and site-specific data for several sensitive parameters. Because the Tier 2 analysis includes site-specific considerations, LCTVs from this analysis are not applicable to other sites.

e. Determination of Liner Designs

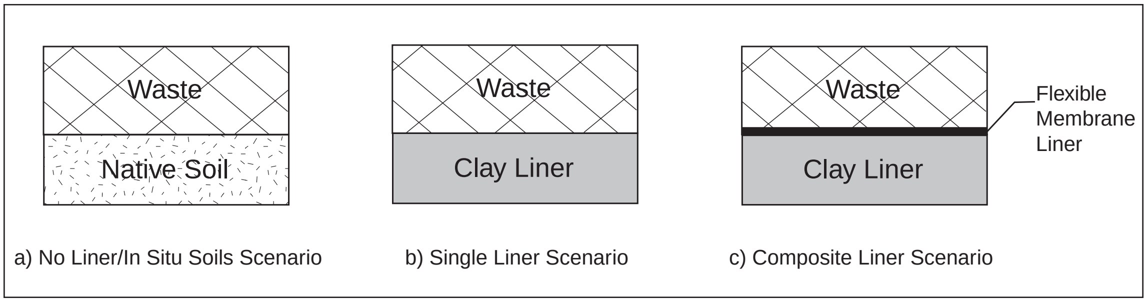
The primary method of controlling the release of waste constituents to the subsurface is to install a low permeability liner at the base of a WMU. A liner generally consists of a layer of clay or other material with a low hydraulic conductivity that is used to prevent or mitigate the flow of liquids from a WMU. The type of liner that is appropriate for a specific WMU, however, is highly dependent upon a number of location-specific characteristics, such as climate and hydrogeology. These characteristics are critical in determining the amount of liquid that migrates into the subsurface from a WMU and in predicting the release of contaminants to ground water.

The IWEM software is intended to assist the user in determining if a new industrial waste management unit can rely on a no liner/in situ soils design, or whether one of the two recommended liners designs, single clay liner or composite liner, should be used. The no liner/in situ soils design (Figure 2a) represents a WMU that relies upon location-specific conditions, such as low permeability native soils beneath the unit or low annual precipitation rates to mitigate the release of contaminants to groundwater. The single clay liner (Figure 2b) design represents a 3-foot thick clay liner with a low hydraulic conductivity ($1x10^{-7}$ cm/sec) beneath a WMU. A composite liner design (Figure 2c) consists of a flexible membrane liner in contact with a clay liner. In Tier 2, users also can evaluate other liner designs by providing a site-specific infiltration rate based on the liner design. For land applications units, only the no liner/in situ soils scenario is evaluated because liners are not typically used at this type of facility.

To determine an appropriate design in Tier 1, IWEM compares expected leachate concentrations for all of the constituents in the leachate to constituent-specific LCTVs and then reports the minimum design system that is protective for all constituents. If the expected leachate concentrations of all waste constituents are lower than their respective no liner/in situ soils LCTVs, the proposed WMU does not need a liner to contain the waste. On the other hand, if the Tier 1 screening evaluation indicates a liner is recommended, a user can verify this recommendation with a follow-up Tier 2 (or possibly Tier 3) analysis for at least those constituents whose expected leachate concentrations exceed the Tier 1 LCTV values.

If the user proceeds to a Tier 2 analysis, IWEM will evaluate the three standard designs or it can evaluate a user-supplied liner design. The user can supply a liner design by providing a site-specific infiltration rate that reflects the expected infiltration rate through the user's liner system. In the Tier 2 analysis, IWEM conducts a location-adjusted Monte Carlo analysis based on user inputs to generate a 90th percentile exposure concentration for the site. The 90th percentile exposure concentration is then compared with the RGC to determine whether a liner is considered necessary, and where appropriate, recommend the design that is protective for each constituent expected in the leachate. If the Tier 2 analysis indicates that the no liner/in situ soils scenario or the user-defined liner is not protective, the user can proceed to a full site-specific Tier 3 analysis.

Figure 2. Three Liner Scenarios Considered in the Tiered Modeling Approach for Industrial Waste Guidelines



B. Tier 1 Evaluations

In a Tier 1 evaluation, IWEM compares the expected leachate concentration for each constituent with the LCTVs calculated for these constituents and determines a minimum recommended design that is protective for all waste constituents. The required inputs are: the type of WMU the user wishes to evaluate, the constituents of concern, and the expected leachate concentrations of constituents of concern. The results for each constituent have been compiled for each unit type and design and are available in the *IWEM Technical Background Document* (U.S. EPA, 2002a) and in the model on the CD-ROM version of this Guide.

The tabulated results for Tier 1 of IWEM have been generated by running the EPACMTP for a wide range of conditions that reflect the varying site conditions that can be expected to occur at waste sites across the United States. The process, which was used to simulate varying site conditions, is known as a Monte Carlo analysis. A Monte Carlo analysis determines the statistical probability or certainty that the release of leachate might result in a ground-water concentration exceeding regulatory or risk-based standards.

For the Tier 1 analysis, 10,000 realizations of EPACMTP were run for each constituent, WMU, and design combination to generate distributions of maximum average exposure concentrations for each constituent by WMU and design. These distributions reflect the variability among industrial waste management units across the United States. The 90th percentile concentration from this distribution was then used to calculate a DAF for each constituent by WMU and design. Each of these DAFs was then combined with constituent-specific RGCs to generate the LCTVs presented

About Monte Carlo Analysis

Monte Carlo analysis is a computer-based method of analysis developed in the 1940s that uses statistical sampling techniques in obtaining a probabilistic approximation to the solution of a mathematical equation or model. The name refers to the city on the French Riviera, which is known for its gambling and other games of chance. Monte Carlo analysis is increasingly used in risk assessments because it allows the risk manager to make decisions based on a statistical level of protection that reflects the variability and/or uncertainty in risk parameters or processes, rather than making decisions based on a single point estimate of risk. For further information on Monte Carlo analysis in risk assessment, see EPA's *Guiding Principles for Monte Carlo Analysis.* (U.S. EPA, 1997b).

in the IWEM software and in the tables included in the technical background document.

The advantages of a Tier 1 screening evaluation are that it is fast, and it does not require site-specific information. The disadvantage of the Tier 1 screening evaluation is that the analysis does not use site-specific information and might result in a design recommendation that is more stringent than is needed for a particular site. For instance, site-specific conditions, such as low precipitation and a deep unsaturated zone, might warrant a less stringent design. Before implementing a Tier 1 recommendation, it is recommended that you also perform a Tier 2 assessment for at least those waste constituents for which Tier 1 indicates that a no liner design is not protective. The following sections provide additional information on how to use the Tier 1 lookup tables.

1. *How Are the Tier 1 Lookup Tables Used?*

The Tier 1 tables provide an easy-to-use tool to assist waste management decision-making. Important benefits of the Tier 1 approach are that it requires minimum data from the user and provides immediate guidance on protective design scenarios. There are only three data requirements for the Tier 1 analysis: WMU type, constituents expected in the waste leachate, and the expected leachate concentration for each constituent in the waste. The Tier 1 tables are able to provide immediate guidance because EPACMTP simulations for each constituent, WMU, and design combinations were run previously for a national-scale assessment to generate appropriate LCTVs for each combination. Because the simulations represent a national-scale assessment, the LCTVs in the Tier 1 tables represent levels in leachate that are protective at most sites.

As noted previously in this chapter, one of the first steps in a ground-water risk assessment is to characterize the waste going into a unit. Characterization of the waste includes identifying the constituents expected in the leachate and estimating leachate concentrations for each of these constituents. Identification of constituents expected in leachate can be based on process knowledge or chemical analysis of the waste. Leachate concentrations can be estimated using process knowledge or an analytical leaching test appropriate to the circumstances, such as the Toxicity Characteristic Leaching Procedure (TCLP). For more information on identifying waste constituents, estimating waste constituent leachate concentrations, and selecting appropriate leaching tests, refer to Chapter 2 — Characterizing Waste.

The following example illustrates the Tier 1 process for evaluating a proposed design for an industrial landfill. The example assumes the expected leachate concentration for toluene is 1.6 mg/L and styrene is 1.0

Information Needed to Use Tier 1 Lookup Tables

Waste management unit types:	Landfill, surface impoundment, waste pile, or land application unit.
Constituents expected in the leachate:	Constituent names and/or CAS numbers.
Leachate concentrations:	Expected leachate concentration of each constituent or concentration in surface impoundments or waste to be applied.

mg/L. Both toluene and styrene have three LCTVs: one based on an MCL, one based on non-cancer ingestion, and one based on non-cancer inhalation. Tables 4 and 5 provide detailed summary information for the no liner/in situ soils scenario for MCL-based LCTVs and the HBN-based LCTVs, respectively, that is similar to the information that can be found in the actual look-up tables.

For the Tier 1 MCL-based analysis presented in Table 4, the results provide the following information: constituent CAS number, constituent name, constituent-specific MCL, user-provided leachate concentration, constituent-specific DAF, the constituent-specific LCTV, and whether the specified design is protective at the target risk level. To provide a recommendation as to whether a specific design is protective or not, IWEM compares the LCTV with the leachate concentration to determine whether the design is protective. In the example presented in Table 4, the no liner/in situ soils scenario is not protective for styrene because the leachate concentration provided by the user (1.0 mg/L) is greater than the Tier 1 LCTV (0.22 mg/L). For toluene, the no liner/in situ soils scenario is protective because the leachate concentration (1.6 mg/L) is less than the Tier 1 LCTV (2.2 mg/L).

For the health-based number (HBN)-based results presented in Table 5, the detailed results present similar information to that presented for the MCL-based results. The differences are that the HBN-results present the constituent-specific HBN rather than the MCL and include an additional column that identifies the pathway and effect that support the development of the LCTV. For the controlling pathway and effect column, IWEM would indicate whether the most protective pathway is ingestion of drinking water (indicated by ingestion) or inhalation during showering (indicated by inhalation) and whether the adverse effect is a cancer or non-cancer effect. In this example, both styrene and toluene have two HBN-based LCTVS: one for ingestion non-cancer and one for inhalation non-cancer. Only the results for the controlling HBN exposure pathway and effect are shown. In Table 5, only the results for the inhalation-during-showering pathway for non-cancer effects are shown because this is the most protective pathway (that is, the LCTV for the inhalation-during-showing pathway is lower than the LCTV for ingestion of drinking water) for both of these constituents. As shown in Table 5, comparison of the leachate concentration of styrene (1.0 mg/L) and toluene (1.6 mg/L) to their respective LCTVs (8.0 mg/L and 2.9 mg/L) indicates that the no liner/in situ soils design is protective for the Tier 1 HBN-based LCTVs.

Based on the results for the no liner/in situ soils scenario, the user could proceed to the comparison of the expected leachate concentration for styrene with the MCL-based LCTV for a single clay liner to determine whether the single clay liner design is protective. The

Table 4:
Example of Tier 1 Summary Table for MCL-based LCTVs for Landfills - No Liner/In situ Soils

CAS #	Constituent	MCL (mg/L)	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Protective?
100-42-5	Styrene	0.1	1.0	2.2	0.22	No
108-88-3	Toluene	1.0	1.6	2.2	2.2	Yes

Table 5:
Example of Tier 1 Summary Table for HBN-based LCTVs for Landfills - No Liner/In situ Soils

CAS #	Constituent	HBN (mg/L)	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Protective?	Controlling Pathway & Effect
100-42-5	Styrene	3.6	1.0	2.2	8.0	Yes	Inhalation Non-cancer
108-88-3	Toluene	1.3	1.6	2.2	2.9	Yes	Inhalation Non-cancer

user also can proceed to a Tier 2 or Tier 3 analysis to determine whether a more site-specific approach might indicate that the no liner/in situ soils design is protective for the site. Table 6 presents the Tier 1 results for the single clay liner. As shown, the single clay liner would not be protective for the MCL-based analysis because the expected leachate concentration for styrene (1.0 mg/L) exceeds the LCTV for styrene (0.61 mg/L). Based on these results, the user could continue on to evaluate whether a composite liner is protective for styrene.

Table 7 presents the results of the Tier 1 MCL-based analysis for a composite liner.[9] A comparison of the leachate concentration for styrene (1.0 mg/L) to the MCL-based LCTV (1000 mg/L) indicates that the composite liner is the recommended liner based on a Tier 1 analysis that will be protective for both styrene and toluene.

2. *What Do the Results Mean and How Do I Interpret Them?*

For the Tier 1 analysis, IWEM evaluates the no liner/in situ soils, single clay liner, and

Table 6:
Example of Tier 1 Summary Table for MCL-based LCTVs for Landfills - Single Clay Liner

CAS #	Constituent	MCL (mg/L)	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Protective?
100-42-5	Styrene	0.1	1.0	6.1	0.61	No
108-88-3	Toluene	1.0	1.6	6.1	6.1	Yes

Table 7:
Example of Tier 1 Summary Table for MCL-based LCTVs for Landfills - Composite Liner

CAS #	Constituent	MCL (mg/L)	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Protective?
100-42-5	Styrene	0.1	1.0	5.4×10^4	1000	Yes
108-88-3	Toluene	1.0	1.6	2.9×10^4	1000	Yes

[9] Table 7 also indicates the effect of the 1000 mg/L cap on the results. The LCTV results from multiplying the RGC with the DAF. In this example, the MCL for styrene (0.1 mg/L) multiplied by the unitless DAF (5.4×10^4) would result in an LCTV of 5,400 mg/L, but because LCTVs are capped, the LCTV for styrene in a composite liner is capped at 1,000 mg/L. See Chapter 6 of the *Industrial Waste Management Evaluation Model Technical Background Document* (U.S. EPA, 2002a) for further information.

composite liner design scenarios, in that order. Generally, if the expected leachate concentrations for all constituents are lower than the no liner LCTVs, the proposed unit does not need a liner to contain this waste. If any expected constituent concentration is higher than the no liner/in situ soils LCTV, a single compacted clay liner or composite liner would be recommended for containment of the waste using the Tier 1 analysis. If any expected concentration is higher than the single clay liner LCTV, the recommendation is at least a composite liner. If any expected concentration is higher than the composite liner LCTV, pollution prevention, treatment, or additional controls should be considered, or a Tier 2 or Tier 3 analysis can be conducted to consider site-specific factors before making a final judgment. For waste streams with multiple constituents, the most protective design that is recommended for any one constituent is the overall recommendation. In the example illustrated in Tables 4, 5, 6, and 7, the recommended design is a composite liner because the expected leachate concentration for styrene exceeds the no liner/in situ soils and clay liner LCTVs in the MCL-based analysis, but is lower than the composite liner LCTV. For the HBN-based analysis, a no liner/in situ soils design would provide adequate protection for the site because, as shown in Table 5, the leachate concentrations for styrene and toluene are lower than their respective HBN-based LCTVs.

The interpretation for land application is similar to the interpretation for landfills. However, only the no liner/in situ soils scenario is evaluated for land application because these types of units generally do not use liner systems. Thus, if all the waste leachate concentrations are below the no liner/in situ soils MCL-based and HBN-based LCTVs in the Tier 1 lookup tables, land-applying waste might be appropriate for the site. If the waste has one or more constituents whose concentrations exceed a land application threshold, the recommendation is that land application might not be appropriate. The model does not consider the other design scenarios.

After conducting the Tier 1 evaluation, users should consider the following steps:

- **Perform additional evaluations.** The Tier 1 evaluation provides a conservative screening assessment whose values are calculated to be protective over a range of conditions and situations. Although a user could elect to install a liner based on the Tier 1 results, it is appropriate that a user consider Tier 2 or Tier 3 evaluations to confirm these recommendations.
- **Consider pollution prevention, recycling, or treatment.** If you do not want to conduct a Tier 2 or Tier 3 analysis, and the waste has one or more "problem" constituents that call for a more stringent and costly design system (or which make land application inappropriate), you could consider pollution prevention, recycling, and treatment options for those constituents. Options that previously might have appeared economically infeasible, might be worthwhile if they can reduce the problem constituent concentration to a level that results in a different design recommendation or would make land application appropriate. Then, after implementing these measures, repeat the Tier 1 evaluation. Based on the results presented in Table 6, pollution prevention, recycling, or treatment measures could be used to reduce the expected leachate concentration for styrene below 0.61 mg/L so that a single liner is recommended for the unit. Consult Chapter 3—Integrating

Pollution Prevention, for ideas and tools.

- **Implement recommendations.** You can design the unit based on the design recommendations of the Tier 1 lookup tables without performing further analysis or considering pollution prevention or recycling activities. In the case of land application, a land application system might be developed (after evaluating other factors) if the lookup tables found no liner necessary for all constituents. In either case, it is recommended that you consult the appropriate agency to ensure compliance with state regulations.

Figure 3 illustrates the basic steps using the Tier 1 lookup tables to determine an appropriate design for a proposed waste management unit or whether land application is appropriate.

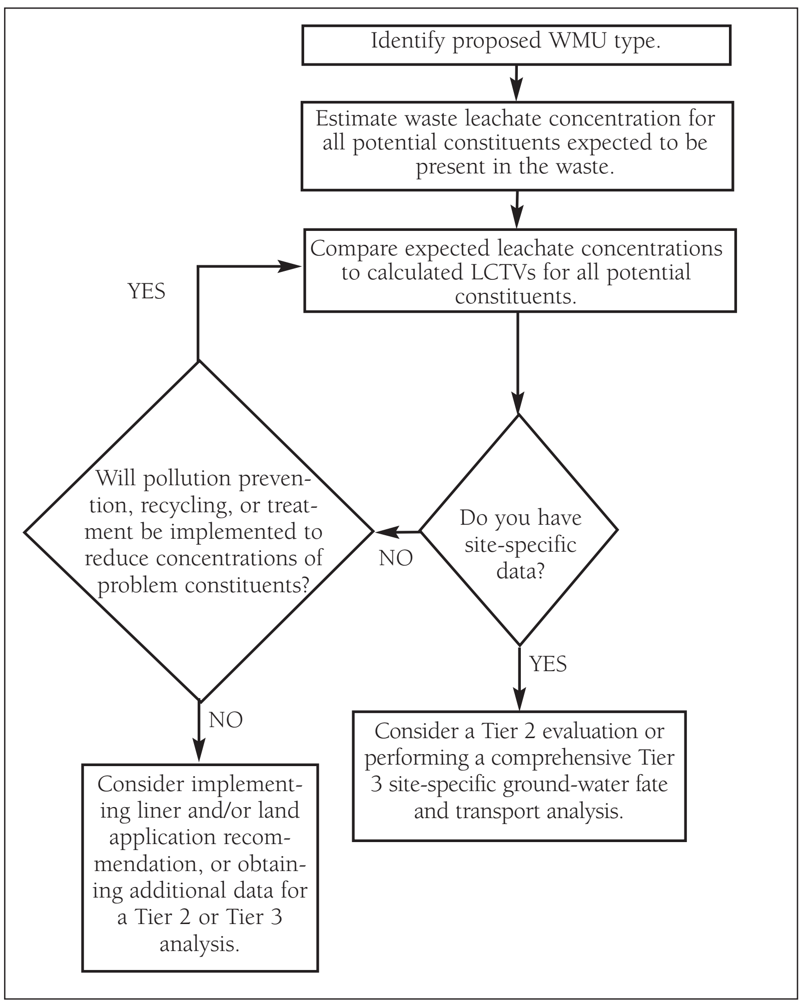
C. Tier 2 Evaluations

The Tier 2 evaluation is designed to provide a more accurate evaluation than Tier 1 by allowing the user to provide site-specific data. In many cases, a Tier 2 evaluation might suggest a less stringent and less costly design than a Tier 1 evaluation would recommend. This section describes the inputs for the analysis and the process for determining a protective recommendation.

1. How is a Tier 2 Analysis Performed?

Under Tier 2, the user can provide site-specific information to refine the design recommendations. The Tier 2 analysis leads the user through a series of data entry screens and then runs EPACMTP to generate a design recommendation based on the site-specific information provided by the user. The user can provide data related to the WMU, the subsurface environment, infiltration rates, physicochemical properties, and toxicity. The user can evaluate the three designs discussed above or provide data reflecting a site-specific

Figure 3. Using Tier 1 Lookup Tables



liner design. As a result, a Tier 2 analysis provides a protective design recommendation intended only for use at the user's site, and is not intended to be applied to other sites. This section discusses the inputs that a user can provide and the results from the analysis.

a. Tier 2 Inputs

In addition to the inputs required for the Tier 1 analysis, a Tier 2 analysis allows users to provide additional inputs that account for attributes that are specific to the user's site. The Tier 2 inputs that are common to the Tier 1 evaluation are:

- WMU type—waste pile, surface impoundment, or land application unit.
- Chemical constituents of concern present in the WMU.
- Leachate concentration (in mg/L) of each constituent.

If the user has already performed a Tier 1 analysis and continues to a Tier 2 analysis, the Tier 1 inputs are carried forward to the Tier 2 analysis. In the Tier 2 analysis, however, the user can change these data without changing the Tier 1 data.

In addition to the Tier 1 inputs, the user also provides values for additional parameters including WMU area, WMU depth for landfills, ponding depth for surface impoundments, and the climate center in the IWEM database that is nearest to the site. These parameters can have a significant influence on the LCTVs generated by the model and also are relatively easy to determine. The user also has the option to provide values for several more parameters. Table 8 presents the list of "required" and "optional" parameters.

Because site-specific data for all of the EPACMTP parameters might not be available, the model contains default values for the "optional" parameters that are used unless the user provides site-specific data. The default values are derived from a number of sources, including a survey of industrial waste management units, a hydrogeologic database, water-balance modeling, and values reported in the scientific literature. The selection of default values is explained in the *IWEM Technical Background Document* (U.S. EPA, 2002a). If site-specific data are available, they should be used to derive the most appropriate design scenario for a particular site.[10]

In addition to the above parameters, users can also enter certain constituent specific properties, as follows:

- **Organic carbon distribution coefficient (K_{OC}).** A function of the nature of a sorbent (the soil and its organic carbon content) and the properties of a chemical (the leachate constituent). It is equal to the ratio of the solid and dissolved phase concentrations, measured in milliliters per gram (mL/g). The higher the value of the distribution coefficient, the higher the adsorbed-phase concentration, meaning the constituent would be less mobile. For metals, IWEM provides an option to enter a site-specific soil-water partition coefficient (K_d), which overrides the MINTEQA2 default sorption isotherms.
- **Degradation coefficient.** The rate at which constituents degrade or decay within an aquifer due to biochemical processes, such as hydrolysis or biodegradation (measured in units of 1/year). The default decay rate in IWEM represents degradation from chemical hydrolysis only, since biodegradation rates are strongly influenced by site-specific factors. In Tier 2, a user can enter an overall

[10] A Tier 2 evaluation is not always less conservative than a Tier 1. For example, if a site has a very large area, a very shallow water table, and/or the aquifer thickness is well below the national average, then the Tier 2 evaluation results can be more stringent than the Tier 1 analysis results.

Table 8.
Input Parameters for Tier 2

Parameter	Description	Use in Model	Units	Applicable WMU	Required or Optional
WMU area	Area covered by the WMU	To determine the area for infiltration of leachate	Square meters (m^2)	All	Required
WMU location	Geographic location of WMU in terms of the nearest of 102 climate stations	To determine local climatic conditions that affect infiltration and aquifer recharge	Unitless	All	Required
Total waste management unit depth	Depth of the unit for landfills (average thickness of waste in the landfill, not counting the thickness of a liner below the waste or the thickness of a final cover on top of the waste) and surface impoundments (depth of the free-standing liquid in the impoundment, not counting the thickness of any accumulated sediment layer at the base of the impoundment)	For landfills, used to determine the landfill depletion rate. For surface impoundments, used as the hydraulic head to derive leakage	Meters (m)	LF SI	Required for landfills and surface impoundments
Depth of waste management unit below ground surface	Depth of the base of the unit below the ground surface	Used together with depth of the water table to determine distance leachate has to travel through unsaturated zone to reach ground water	Meters (m)	LF SI WP	Optional
Surface Impoundment sediment layer thickness	Thickness of sediment at the base of surface impoundment (discounting thickness of engineered liner, if present)	Limits infiltration from unit.	Meters (m)	SI	Optional
WMU operational life	Period of time WMU is in operation.	IWEM assumes leachate generation occurs over the same period of time.	Years	WP SI LAU	Optional
WMU infiltration rate	Rate at which leachate flows from the bottom of a WMU (including any liner) into unsaturated zone	Affected by area's rainfall intensity and design performance. Users either input infiltration rates directly or allow IWEM to estimate values based on the unit's geographic location,[11] liner design, cover design and WMU type.	Meters per year (m/yr)	All	Optional
Soil type	Predominant soil type in the vicinity of the WMU	Uses site-specific soil data to model leachate migration through unsaturated zone and determine regional recharge rate	sandy loam silt loam silty clay loam	All	Optional
Distance to a well	The distance from a WMU to a downgradient well.	To determine the horizontal distance over which dilution and attenuation occur.	Meters (m)	All	Optional
Hydrogeological setting	Information on the hydrogeological setting of the WMU	Determines certain aquifer characteristics (depth to water table, saturated zone thickness, saturated zone hydraulic conductivity, ground-water hydraulic gradient) when complete information not available	Varies	All	Optional

[11] For surface impoundments IWEM can use either the unit's geographic location or impoundment characteristics (such as ponding depth, and thickness of sediment layer) to estimate the infiltration rates.

Table 8.
Input Parameters for Tier 2 (con't)

Parameter	Description	Use in Model	Units	Applicable WMU	Required or Optional
Depth to the water table	The depth of the zone between the land surface and the water table	Used to predict travel time.	Meters (m)	All	Optional
Saturated zone thickness	Thickness of the saturated zone of the aquifer	Delineates the depth over which leachates can mix with ground waters.	Meters (m)	All	Optional
Saturated zone hydraulic conductivity	Hydraulic conductivity of the saturated zone, or the permeability of the saturated zone in the horizontal direction.	With hydraulic gradient, used to calculate ground-water flow rates.	Meters per year (m/yr)	All	Optional
Ground-water hydraulic gradient	Regional horizontal ground-water gradient	With hydraulic conductivity, used to calculate the ground-water flow rate.	Meters per meter (m/m)	All	Optional
Distance to nearest surface water body	The distance from the unit to the nearest water body	Affects the calculation of ground-water mounding at a site	Meters (m)	SI	Optional

degradation rate which overrides the IWEM default. A user can choose to include degradation due to hydrolysis and biodegradation in the overall degradation rate.

b. *Tier 2 Results*

After providing site-specific inputs, the user generates design recommendations for each constituent by launching EPACMTP from within IWEM. EPACMTP will then simulate the site and determine the 90th percentile exposure concentration for each design scenario. IWEM determines the minimum recommended design at a 90th percentile exposure concentration by performing 10,000 Monte Carlo simulations of EPACMTP for each waste constituent and design. Upon completion of the modeling analyses, IWEM will display the minimum design recommendation and the calculated, location-specific LCTVs based on the 90th percentile exposure concentration.

The overall result of a Tier 2 analysis is a design recommendation similar to the Tier 1 analysis. However, the basis for the recommendation differs slightly. To illustrate the similarities and differences between the results from the two tiers, the remainder of this section continues the example Tier 1 evaluation through a Tier 2 evaluation. In the Tier 1 example, the disposal of toluene and styrene in a proposed landfill is evaluated. The expected leachate concentration for toluene is 1.6 mg/L and the expected leachate concentration for styrene is 1.0 mg/L. In Tier 2, after inputting the site-specific data summarized in Table 9 and using default data for the remaining parameters, the user can then launch the EPACMTP model simulations.

After completing the EPACMTP model simulations, IWEM produces the results on screen. Table 10 presents the detailed results of a Tier 2 analysis for the no liner/in situ soils scenario. The data presented in this table are similar to the data presented in the Tier 1 results, but the Tier 2 analysis expands

Table 9.
A Sample Set of Site-Specific Data for Input to Tier 2

Parameters	Site-Specific Data
Infiltration rate*	Local climate: Madison, WI Soil type: fine-grained soil
Waste management unit area	15,000 m^2
Waste management unit depth	2 m
Depth to the water table	10 m
Aquifer thickness	25 m
Toxicity standards	Compare to all
Distance to a well	150 m

* The Tier 2 model uses an infiltration rate for the liner scenarios based on local climate and soil data.

the information provided to the user. It includes additional information regarding the toxicity standard, the reference ground-water concentration (RGC), and the 90th percentile exposure concentration. The toxicity standard is included because the user can select specific standards, provide a user-defined standard, or compare to all standards. In this example, all standards were selected; the user can identify the result for each standard from a single table. The LCTV continues to represent the maximum leachate

Table 10:
Example of Tier 2 Detailed Summary Table - No Liner/In situ Soils

CAS #	Constituent	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Toxicity Standard	Ref. Ground-water Conc. (mg/L)	90th Percentile Exposure Concentration (mg/L)	Protective?
100-42-5	Styrene	1.0	8.3	0.83	MCL	0.1	0.1201	No
100-42-5	Styrene	1.0	8.3	29.88	HBN - Ingestion Non-Cancer	3.6	0.1201	Yes
100-42-5	Styrene	1.0	8.3	40.67	HBN - Inhalation Non-cancer	4.9	0.1201	Yes
108-88-3	Toluene	1.6	8.3	8.3	MCL	1	0.1922	Yes
108-88-3	Toluene	1.6	8.4	10.92	HBN - Ingestion Non-cancer	1.3	0.1894	Yes
108-88-3	Toluene	1.6	8.4	41.16	HBN - Inhalation Non-cancer	4.9	0.1894	Yes

concentration for a design scenario that is still protective for a reference ground-water concentration, but the LCTV is not the basis for the design recommendation.

The RGC and 90th percentile exposure concentration are provided because they are the point of comparison for the Tier 2 analysis. (The LCTV, however, continues to provide information about a threshold that might be useful for pollution prevention or waste minimization efforts.) As shown in Table 10, the no liner/in situ soils scenario is protective for toluene because all of the 90th percentile exposure concentrations are less than the three RGCs for toluene, while the no liner/in situ soils scenario is not protective for styrene for the MCL comparison. For that standard, the 90th percentile exposure concentration (0.1201 mg/L) exceeds the RGC (0.1 mg/L). In this case, IWEM would launch EPACMTP to evaluate a clay liner to determine whether that liner design would be protective.

Table 11 provides the single clay liner results for a Tier 2 analysis. As shown in the table, the single clay liner is protective because the 90th percentile exposure concentration (0.0723 mg/L) is less than the reference ground-water concentration (0.1 mg/L). In addition, under the "Protective?" column, IWEM refers the user to the appropriate liner result if a less stringent design is recommended. In Table 11, the user is referred to the no liner/in situ soils results for the HBN-based ingestion and inhalation results because, as shown in Table 10, the no liner/in situ soils scenario is protective. If a Tier 2 analysis determines that a single clay liner is protective for all constituents, then IWEM would not continue to an evaluation of a composite liner. For this example of styrene and toluene disposed of in a landfill, the recommended minimum design is a single clay liner, because the 90th percentile exposure concentration (0.0723) is less than the MCL-based RGC (0.1).

2. *What Do the Results Mean and How Do I Interpret Them?*

The Tier 2 analysis provides LCTVs and recommendations for a minimum protective design. In the Tier 1 analysis, that recommendation is based on a comparison of expected leachate concentrations to LCTVs to determine whether a design scenario is protective. In the

Table 11:
Example of Tier 2 Detailed Summary Table - Single Clay Liner

CAS #	Constituent	Leachate Concentration (mg/L)	DAF	LCTV (mg/L)	Toxicity Standard	Ref. Ground-water Conc. (mg/L)	90th Percentile Exposure Concentration (mg/L)	Protective?
100-42-5	Styrene	1.0	14	1.4	MCL	0.1	0.0723	Yes
100-42-5	Styrene	1.0	14	50.4	HBN - Ingestion Non-Cancer	3.6	0.0722	See No liner Results
100-42-5	Styrene	1.0	14	68.6	HBN - Inhalation Non-cancer	4.9	0.0722	See No liner Results

Tier 2 analysis, LCTVs can be used to help waste managers determine whether waste minimization techniques might lower leachate concentrations and enable them to use less costly unit designs, but IWEM does not need to calculate an LCTV to make a design recommendation. If the 90th percentile ground-water concentration does not exceed the specified RGC, then the evaluated design scenario is protective for that constituent. If the 90th percentile ground-water concentrations for all constituents under the no liner/in situ soils scenario are below their respective RGCs , then IWEM will recommend that no liner/in situ soils is needed to protect the ground water. If the 90th percentile ground-water concentration of any constituent exceeds its RGC, then a single clay liner is recommended (or, in the case of land application units, land application is not recommended). Similarly, if the 90th percentile ground-water concentration of any constituent under the single clay liner scenario exceeds its RGC, then a composite liner is recommended. As previously noted, however, you may decide to conduct a Tier 3 site-specific analysis to determine which design scenario is most appropriate. See the ensuing section on Tier 3 analyses for further information. For waste streams with multiple constituents, the most protective liner design that is recommended for any one constituent is the overall recommendation. As in the Tier 1 evaluation, pollution prevention, recycling, and treatment practices could be considered when the protective standard of a composite liner is exceeded if you decide not to undertake a Tier 3 assessment to reflect site-specific conditions.

If the Tier 2 analysis found land application to be appropriate for the constituents of concern, then a new land application system may be considered (after evaluating other factors). Alternatively, if the waste has one or more "problem" constituents that make land application inappropriate, the user might consider pollution prevention, recycling, and treatment options for those constituents. If, after conducting the Tier 2 evaluation, the user is not satisfied with the resulting recommendations, or if site-specific conditions seem likely to suggest a different conclusion regarding the appropriateness of land application of a waste, then the user can conduct a more in-depth, site-specific, ground-water risk analysis (Tier 3).

In addition to the Tier 2 evaluation, other fate and transport models have been developed that incorporate location-specific considerations, such as the American Petroleum Institute's (API's) *Graphical Approach for Determining Site-Specific Dilution-Attenuation Factors.*[12] API developed its approach to calculate facility-specific DAFs quickly using graphs rather than computer models. Graphs visually indicate the sensitivity to various parameters. This approach can be used for impacted soils located above or within an aquifer. This approach accounts for attenuation with distance and time due to advective/dispersive processes. API's approach has a preliminary level of analysis that uses a small data set containing only measures of the constituent plume's geometry. The user can read other necessary factors off graphs provided as part of the approach. This approach also has a second level of analysis in which the user can expand the data set to include site-specific measures, such as duration of constituent leaching, biodegradation of constituents, or site-specific dispersivity values. At either level of analysis, the calculation results in a DAF. This approach is not appropriate for all situations; for example, it should not be used to estimate constituent concentrations in active ground-water supply wells or to model very complex hydrogeologic settings, such as fractured rock. It is recommended that you consult with the appropriate state agency to discuss the applicability of the API approach or any other location-adjusted model prior to use.

[12] A copy of API's user manual, *The Technical Background Document and User Manual (API Publication 4659)*, can be obtained from the American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005, 202 682-8375.

D. Strengths and Limitations

Listed below are some of IWEM's strengths and limitations that the user should be aware of:

1. *Strengths*

- The tool is relatively easy to use and requires a minimal amount of data and modeling expertise.
- The tool can perform rapid Tier 1 screening evaluations. Tier 2 evaluations allow for many site-specific adjustments.
- The tool is designed to be flexible with respect to the availability of site-specific data for a Tier 2 evaluation. The user needs to provide only a small number of inputs, but if more data are available, the tool can accommodate their input.
- Users can enter their own infiltration rates to evaluate additional design scenarios and still use IWEM to conduct a risk evaluation.
- The user can modify RGC values, when appropriate, and in consultation with other stakeholders.
- The user can modify properties of the 226 constituents (e.g., adding biodegradation), and can add additional constituents for evaluation.
- The tool provides recommendations for protective design systems. It can also be used to evaluate whether waste leachate reduction measures would be appropriate.

2. *Limitations*

- IWEM considers only exposures from contact with contaminated ground water via ingestion of drinking water and inhalation while showering. IWEM does not consider vapor intrusion into buildings. It also does not address potential risks through environmental pathways other than ground water, such as volatile emissions from a WMU, surface runoff and erosion, and indirect exposures through the food chain pathway. Other chapters in this Guide, however, address ways to assess or control potential risks via such other pathways.
- The use of a waste concentration to leachate concentration ratio of 10,000 in IWEM Tier 2 may overestimate the amount of contaminant mass in the WMU, allowing the modeling results to approach non-depleting source steady-state values for WMUs without engineered liners. This may result in an underestimation of the Tier 2 LCTVs.
- IWEM considers only human health risks. Exposure and risk to ecological receptors are not included.
- The conceptual flow model used in EPACMTP in conjunction with IWEM Tier 2 data input constraints might produce ground-water velocities that might be greater than can be assumed based on the site-specific hydraulic conductivity and hydraulic gradient values. The maximum values that the velocities can reach are limited by a model constraint that appropriately prevents the modeled water level from rising above the ground surface. Despite this constraint, modeled velocities might be greater than expected velocities based on site-specific hydraulic conductivity and hydraulic gradient.

- The risk evaluation in IWEM is based on the ground-water concentration of individual waste constituents. IWEM does not address the cumulative risk due to simultaneous exposure to multiple constituents (although it does use a carcinogenic risk level at the conservative end of EPA's risk range).
- IWEM is not designed for sites with complex hydrogeology, such as fractured (karst) aquifers.
- The tool is inappropriate for sites where non-aqueous phase liquid (NAPL) contaminants are present.
- IWEM does not account for all possible fate and transport processes. For example, colloid transport might be important at some sites but is not considered in IWEM. While the user can enter a constituent-specific degradation rate constant to account for biodegradation, IWEM simulates biodegradation in a relatively simple way by assuming the rate is the same in both the unsaturated and the saturated zones.

E. Tier 3: A Comprehensive Site-Specific Evaluation

If the Tier 1 and Tier 2 evaluations do not adequately simulate conditions at a proposed site, or if you decide that sufficient data are available to skip a Tier 1 or Tier 2 analysis, a site-specific risk assessment could be considered.[13] In situations involving a complex hydrogeologic setting or other site-specific factors that are not accounted for in IWEM, a detailed site-specific ground-water fate and transport analysis might be appropriate for determining risk to ground water and evaluating alternative designs or application rates. It is recommended that you consult with the appropriate state agency and use a qualified professional experienced in ground-water modeling. State officials and appropriate trade associations might be able to suggest a good consultant to perform the analysis.

Why is it important to use a qualified professional?

- Fate and transport modeling can be very complex; appropriate training and experience are required to correctly use and interpret models.
- Incorrect fate and transport modeling can result in a liner system that is not sufficiently protective or an inappropriate land application rate.
- To avoid incorrect analyses, check to see if the professional has sufficient training and experience at analyzing ground-water flow and contaminant fate and transport.

1. *How is a Tier 3 Evaluation Performed?*

A Tier 3 evaluation will generally involve a more detailed site-specific analysis than Tier 2. Sites for which a Tier 3 evaluation might be performed typically involve complex and heterogeneous hydrogeology. Selection and application of appropriate ground-water models require a thorough understanding of the waste and the physical, chemical, and hydrogeologic characteristics of the site.

A Tier 3 evaluation should involve the following steps:

- Developing a conceptual hydrogeological model of the site.
- Selecting a flow and transport simulation model.
- Applying the model to the site.

[13] For example, if ground-water flow is subject to seasonal variations, use of the Tier 2 evaluation tool might not be appropriate because the model is based on steady-state flow conditions.

As with all modeling, you should consult with the state before investing significant resources in a site-specific analysis. The state might have a list of preferred models and might be able to help plan the fate and transport analysis.

a. *Developing a Conceptual Hydrogeological Model*

The first step in the site-specific Tier 3 evaluation is to develop a conceptual hydrogeological model of the site. The conceptual model should describe the key features and characteristics to be captured in the fate and transport modeling. A complete conceptual hydrogeological model is important to ensure that the fate and transport model can simulate the important features of the site. The conceptual hydrogeological model should address questions such as:

- Does a confined aquifer, an unconfined aquifer, or both need to be simulated?
- Does the ground water flow through porous media, fractures, or a combination of both?
- Is there single, or are there multiple, hydrogeologic layers to be simulated?
- Is the hydrogeology constant or variable in layer thickness?
- Are there other hydraulic sources or sinks (e.g., extraction or injection wells, lakes, streams, ponds)?
- What is the location of natural no-flow boundaries and/or constant head boundaries?
- How significant is temporal (seasonal) variation in ground-water flow conditions? Does it require a transient flow model?
- What other contaminant sources are present?
- What fate processes are likely to be significant (e.g. sorption and biodegradation)?
- Are plume concentrations high enough to make density effects significant?

b. *Selecting a Fate and Transport Simulation Model*

Numerous computer models exist to simulate ground-water fate and transport. Relatively simple models are often based on analytical solutions of the mathematical equations governing ground-water flow and solute transport equations. However, such models generally cannot simulate the complexities of real world sites, and for a rigorous Tier 3 evaluation, numerical models based on finite-difference or finite-element techniques are recommended. The primary criteria for selecting a particular model should be that it is consistent with the characteristics of the site, as described in the conceptual site hydrogeological model, and that it is able to simulate the significant processes that control contaminant fate and transport.

In addition to evaluating whether a model will adequately address site characteristics, the following questions should be answered to ensure that the model will provide accurate, verifiable results:

- What is the source of the model? How easy is it to obtain and is the model well documented?
- Are documentation and user's manuals available for the model? If yes, are they clearly written and do they provide sufficient technical background on the mathematical formulation and solution techniques?

What are some useful resources for selecting a ground-water fate and transport model?

The following resources can help select appropriate modeling software:

- *Ground Water Modeling Compendium*, Second Edition (U.S. EPA, 1994c)
- *Assessment Framework for Ground-Water Modeling Applications* (U.S. EPA, 1994b)
- *Technical Guide to Ground-water Model Selection at Sites Contaminated with Radioactive Substances* (U.S. EPA, 1994a)
- *EPA's Center for Subsurface Modeling Support* (CSMoS—RSKERL; Ada, Oklahoma)
- Anderson, Mary P. and William W. Woessner. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (Academic Press, 1992)
- EPA regional offices

- Has the model been verified against analytical solutions and other models? If yes, are the test cases available so that a professional consultant can test the model on his/her computer system?
- Has the model been validated using field data?

Table 12 provides a brief description of a number of commonly used ground-water fate and transport models.

c. *Applying the Model to the Site*

For proper application of a ground-water flow and transport model, expertise in hydrogeology and the principles of flow and transport, as well as experience in using models and interpreting model results are essential. The American Society for Testing and Materials (ASTM) has developed guidance that might be useful for conducting modeling. A listing of guidance material can be found in Table 13.

The first step in applying the model to a site is to calibrate it. Model calibration is the process of matching model predictions to observed data by adjusting the values of input parameters. In the case of ground-water modeling, the calibration is usually done by matching predicted and observed hydraulic head values. Calibration is important even for well-characterized sites, because the values of measured or estimated model parameters are always subject to uncertainty. Calibrating the flow model is usually achieved by adjusting the value(s) of hydraulic conductivity and recharge rates. In addition, if plume monitoring data or tracer test data are available, transport parameters such as dispersivity, and sorption and degradation parameters can also be calibrated. A properly calibrated model is a powerful tool for predicting contaminant fate and transport. Conversely, if no calibration is performed due to lack of suitable site data, any Tier 3 model predictions will remain subject to considerable uncertainty.

At a minimum, a site-specific analysis should provide estimated leachate concentrations at specified downgradient points for a proposed design. For landfills, surface impoundments and waste piles, you should compare these concentrations to appropriate MCLs, health-based standards, or state standards. For land application units, if a waste leachate concentration is below the values specified by the state, land application might be appropriate. Conversely, if a leachate concentration is above state-specified values, land application might not be protective of the ground water.

Table 12.
Example Site-Specific Ground-Water Fate and Transport Models

Model Name	Description
MODFLOW	MODFLOW is a 3-D, ground-water flow model for steady state and transient simulation of saturated flow problems in confined and unconfined aquifers. It calculates flow rates and water balances. The model includes flow towards wells, through riverbeds, and into drains. MODFLOW is the industry standard for ground-water modeling that was developed and still maintained by the United States Geological Survey (USGS). MODFLOW-2000 is the current version. MODFLOW is a public domain model; numerous pre- and post-processing software packages are available commercially. MODFLOW can simulate ground-water flow only. In order to simulate contaminant transport, MODFLOW must be used in conjunction with a compatible solute transport model (MT3DMS, see below). MODFLOW and other USGS models can be obtained from the USGS Web site at **<water.usgs.gov/nrp/gwsoftware/modflow.html>**.
MT3DMS	Modular 3-D Transport model (MT3D) is commonly used in contaminant transport modeling and remediation assessment studies. Originally developed for EPA, the current version is known as MT3DMS. MT3DMS has a comprehensive set of options and capabilities for simulating advection, dispersion/diffusion, and chemical reactions of contaminants in ground-water flow systems under general hydrogeologic conditions. MT3DMS retains the same modular structure of the original MT3D code, similar to that implemented in MODFLOW. The modular structure of the transport model makes it possible to simulate advection, dispersion/diffusion, source/sink mixing, and chemical reactions separately without reserving computer memory space for unused options. New packages involving other transport processes and reactions can be added to the model readily without having to modify the existing code. NOTE: The original version of this model known as MT3D, released in 1991, was based on a mathematical formulation which could result in mass-balance errors. This version should be avoided. MT3DMS is maintained at the University of Alabama, and can be obtained at: **<hydro.geo.ua.edu/mt3d>**. MT3DMS is also included, along with MODFLOW, in several commercial ground-water modeling software packages.
BIOPLUME-III	BIOPLUME-III is a 2-D, finite difference model for simulating the natural attenuation of organic contaminants in ground water due to the processes of advection, dispersion, sorption, and biodegradation. Biotransformation processes are potentially important in the restoration of aquifers contaminated with organic pollutants. As a result, these processes require valuation in remedial action planning studies associated with hydrocarbon contaminants. The model is based on the USGS solute transport code MOC. It solves the solute transport equation six times to determine the fate and transport of the hydrocarbons, the electron acceptors (O_2, NO^{3-}, Fe^{3+}, SO_4^{2-}, and CO_2), and the reaction byproducts (Fe^{2+}). A number of aerobic and anaerobic electron acceptors (e.g., oxygen, nitrate, sulfate, iron (III), and carbon dioxide) have been considered in this model to simulate the biodegradation of organic contaminants. Three different kinetic expressions can be used to simulate the aerobic and anaerobic biodegradation reactions. BIOPLUME-III and other EPA supported ground-water modeling software can be obtained via the EPA Center for Subsurface Modeling Support at the RS Kerr Environmental Research Lab in Ada, Oklahoma: **<www.epa.gov/ada/csmos/models.html>**.

A well-executed site-specific analysis can be a useful instrument to anticipate and avoid potential risks. A poorly executed site-specific analysis, however, could over- or under-emphasize risks, possibly leading to adverse human health and environmental effects, or costly cleanup liability, or it could overemphasize risks, possibly leading to the unnecessary expenditure of limited resources. If possible, the model and the results of the final analyses, including input and output parameters and key assumptions, should be shared with stakeholders. Chapter 1—Understanding Risk and Building Partnerships provides a more detailed description of activities to keep the public informed and involved.

Table 13. ASTM Ground-Water Modeling Standards

The American Society for Testing and Materials (ASTM), Section D-18.21.10 concerns subsurface fluid-flow (ground-water) modeling. The ASTM ground-water modeling section is one of several task groups funded under a cooperative agreement between USGS and EPA to develop consensus standards for the environmental industry and keep the modeling community informed as to the progress being made in development of modeling standards.

The standards being developed by D-18.21.10 are "guides" in ASTM terminology, which means that the content is analogous to that of EPA guidance documents. The ASTM modeling guides are intended to document the state-of-the-science related to various topics in subsurface modeling.

The following standards have been developed by D-18.21.10 and passed by ASTM. They can be purchased from ASTM by calling 610 832-9585. To order or browse for publications, visit ASTM's Web site **<www.astm.org>** .

D-5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem

D-5490 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information

D-5609 Guide for Defining Boundary Conditions in Ground-Water Flow Modeling

D-5610 Guide for Defining Initial Conditions in Ground-Water Flow Modeling

D-5611 Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application

D-5718 Guide for Documenting a Ground-Water Flow Model Application

D-5719 Guide to Simulation of Subsurface Air Flow Using Ground-Water Flow Modeling Codes

D-5880 Guide for Subsurface Flow and Transport Modeling

D-5981 Guide for Calibrating a Ground-Water Flow Model Application

A compilation of most of the current modeling and aquifer testing standards also can be purchased. The title of the publication is *ASTM Standards on Analysis of Hydrologic Parameters and Ground Water Modeling*, publication number 03-418096-38.

For more information by e-mail, contact **service@astm.org**.

Assessing Risk Activity List

- ❑ Review the risk characterization tools recommended by this chapter.
- ❑ Characterize the waste in accordance with the recommendations of Chapter 2 — Characterizing Waste.
- ❑ Obtain expected leachate concentrations for all relevant waste constituents.
- ❑ If a Tier 1 evaluation is conducted, understand and use the Tier 1 Evaluation to obtain recommendations for the design of your waste management unit (as noted previously, you can skip the Tier 1 analysis and proceed directly to a Tier 2 or Tier 3 analysis).
- ❑ If a design system or other measures are recommended in a Tier 1 analysis, perform a Tier 2 analysis if you believe the recommendations are overly protective. Also, if data are available, you can conduct a Tier 2 or Tier 3 analysis without conducting a Tier 1 evaluation.
- ❑ If your site characteristics or your waste management needs are particularly complex, or do not adequately simulate conditions reflected in a Tier 1 or Tier 2 analysis, consult with your state and a qualified professional and consider a more detailed, site-specific Tier 3 analysis.

Resources

ASTM. 1996. ASTM Standards on Analysis of Hydrologic Parameters and Ground Water Modeling, Publication Number 03-418096-38.

ASTM. 1993. D-5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem.

ASTM. 1993. D-5490 Guide for Comparing Ground-Water Flow Model Simulations to Site-specific Information.

ASTM. 1994. D-5609 Guide for Defining Boundary Conditions in Ground-Water Flow Modeling.

ASTM. 1994. D-5610 Guide for Defining Initial Conditions in Ground-Water Flow Modeling.

ASTM. 1994. D-5611 Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application.

ASTM. 1994. D-5718 Guide for Documenting a Ground-Water Flow Model Application.

ASTM. 1994. D-5719 Guide to Simulation of Subsurface Air Flow Using Ground-Water Flow Modeling Codes.

ASTM. 1995. D-5880 Guide for Subsurface Flow and Transport Modeling.

ASTM. 1996. D-5981 Guide for Calibrating a Ground-Water Flow Model Application.

Bagchi, A. 1994. Design, Construction, and Monitoring of Landfills.

Berner, E. K. and R. Berner. 1987. The Global Water Cycle: Geochemistry and Environment.

Boulding, R. 1995. Soil, Vadose Zone, and Ground-Water Contamination: Assessment, Prevention, and Remediation.

Lee, C. 1992. Environmental Engineering Dictionary, 2d. Ed.

Sharma, H., and S. Lewis. 1994. Waste Containment Systems, Waste Stabilization, and Landfills.

Speidel, D., L. Ruedisili, and A. Agnew. 1988. Perspectives on Water: Uses and Abuses.

Resources (cont.)

U.S. EPA. 2002a. Industrial Waste Management Evaluation Model (IWEM) Technical Background Document. EPA530-R-02-012.

U.S. EPA. 2002b. The User's Guide for the Industrial Waste Management Evaluation Model. EPA530-R- 02-013.

U.S. EPA. 2002c. EPACMTP Data/Parameters Background Document.

U.S. EPA. 2002d. EPACMTP Technical Background Document.

U.S. EPA. 1997a. Exposure Factors Handbook. EPA600-P-95-002F.

U.S. EPA. 1997b. Guiding Principles for Monte Carlo Analyses. EPA630-R-97-001.

U.S. EPA. 1994a. A Technical Guide to Ground-Water Model Selection at Sites Contaminated with Radioactive Substance. EPA 4-2-R-94-012.

U.S. EPA. 1994b. Assessment Framework for Ground-Water Modeling Applications. EPA500-B-94-003.

U.S. EPA. 1994c. Ground-Water Modeling Compendium, Second Edition. EPA500-B-94-003.

U.S. EPA. 1991. Seminar Publication: Site Characterization for Subsurface Remediation. EPA625-4-91-026.

U.S. EPA. 1989. Exposure Assessment Methods Handbook.

U.S. EPA. 1988. Selection Criteria For Mathematical Models Used In Exposure Assessments: Ground-water Models. EPA600-8-88-075.

U.S. EPA. 1988. Superfund Exposure Assessment Manual.